The 23rd World
Congress of Soil Science

# The 23rd World Congress of Soil Science

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# Abstracts

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# The Comparative Investigation of Soil Morphological Organization in Polar Urals (Yamal, Russia) and Qilian Mountains (Qinghai-Tibet Plateau, China)

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## ABSTRACT

In this report, we compared the soils of two geographically and climatically different mountainous regions located in the permafrost zone: the Polar Urals (Yamal region of Russia, catena No. 1, C1) and the Qilian Mountains (Qinghai-Tibet Plateau, China, catena No. 2, C2). The two completely different regions of permafrost distribution were compared to understand the diversity of permafrost-affected soils and cryogenic ecosystems and further develop strategies for managing soil and biological resources in a changing climate. While peaks of the Qilian Mountains are over 5,000 meters high, the soil and vegetation belt here is usually distributed at the altitudes of 3,500-4,500 meters, giving way to rocks and mountain glaciers. In the Polar Urals, the soil and vegetation belt appears an average of 900 meters, where it is interspersed with open rock formations and glaciers, which are gradually disappearing. In addition to climate, the most important predictors of soil diversity in the studied regions are geogenic factors—soil-forming parent materials and relief. Despite several high peaks in the Qilian Mountains, there are vast areas with gentle slopes and eroded valleys, often covered with thick layers of diluvium, colluvium, loess and loess-like deposits, sporadically underlain by permafrost at depth more than 1 m. The mountain ridges of the Polar Urals are characterized by steeper slopes with less pronounced terraces. Slope deposits (colluvium, diluvium and talus deposits) are more developed, and the permafrost table is often located at a depth of 20-30 cm from the surface soil horizon. Thus, the depth of the active layer and the thickness of the fine-earth soil layer in the profiles are the main features that distinguish C1 from C2. The C1 sequence of the soils from the top of the ridge to the bottom of the slope includes following soil types: Leptosols, Cambisols, Cryosols (within one altitudinal belt) and Cryosols with specific caviar like structure (Cryomorphic soils). All the C1 soils are Hyperskeletic. The C2 soil sequence consists of Leptosols, Histic Cryosols, Cambisols, Mollic Cryosols, Podzols. Thus, under other equal conditions, the most developed solums are found in the soils of the C2, while soil development in depth in the C1 is limited by the high stoniness of the parent material and the shorter warm season.

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# Quantitative analysis of soil erosion crack dimensions caused by wind-driven rainfall using image processing

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## ABSTRACT

In recent decades, soil erosion has become a major environmental crisis, profoundly impacting ecosystems and natural resources (Sadeghi et al., 2025). This phenomenon has led to soil degradation and reduced fertility. Soil erosion is caused by the interaction of effective factors, including climate, soil erodibility, topography, soil management, conservation practices, and vegetation cover (Kiani-Harchegani et al., 2019; Dash & Maity, 2023; Badapalli et al., 2025). Among the factors affecting soil erosion, climatic and topographic factors are considered as important dynamic and static variables in soil erosion and sediment yield. Important topographic features include slope steepness and direction, and climatic features include rainfall, snow, and wind. These factors, directly or indirectly, affect other environmental factors, thereby altering soil hydrological processes. In calm, no-wind conditions, raindrops usually strike the ground vertically. Since wind is the driving force behind natural rainstorms, it can affect rainfall rates. Accordingly, wind-driven rainfall (WDR) can alter the characteristics of raindrops, including diameter, velocity, area, drop angle, and kinetic energy (Kalehhouei et al., 2023). The effect of this set of factors increases stress and activity in the surface soil aggregates, leading to the formation of cracks and rills on the soil surface. Accordingly, understanding the complex interactions between wind and rainfall is essential for monitoring and analyzing changes in water erosion. In this regard, the present study investigates the effect of WDR at different slopes and wind velocities. For the experiment, sandy-loam topsoil samples were collected to a depth of 20 cm from summer rangeland located in the Kojour watershed on the northern slopes of the Alborz Mountain in IRAN. After that, the prepared soil was transferred to three experimental plots measuring 6 m2 each. The soil surface of each plot was compacted with a hand roller to reach a bulk density of 1.46 g cm−3. For rainfall simulation, a rainfall intensity of 50 mm h-1 and a duration of 30 min were determined for a 30-year return period based on the intensity-duration-frequency (IDF) curves of Kojour Synoptic Station. Wind simulation was performed using two 1×1 m wind blowers, and the wind velocity produced by each was monitored with an anemometer. According to the wind rose of the synoptic station of the Kojour watershed, the prevailing wind velocity and direction in the region were approximately 2.9 m s-1 and northward. Wind velocities of 3 and 6 m s-1 were selected based on the experimental conditions and the possibility of wind generation. The wind direction in the experimental conditions was set to be upward. The characteristics of the cracks on the soil surface were measured after simulation using Digimizer software (Kalehhouei et al., 2025). Changes in raindrop characteristics at a 12% slope showed that, in no-wind conditions, the mean length, width, area, and perimeter of each soil surface crack were 6.04 cm, 4.72 cm, 20.18 cm2, and 18.67 cm, respectively. In contrast, the study properties under wind velocity of 3 m s-1 reached 7.32 cm, 4.96 cm, 25.47 cm2, and 20.12 cm, respectively. Similarly, under a wind velocity of 6 m s-1, the study characteristics increased to 10.14 cm, 7.65 cm, 33.21 cm2, and 26.83 cm. Also, results from changes in raindrop characteristics at a 30% slope showed that, in no-wind conditions, the mean length, width, area, and perimeter of each soil surface crack were 8.88 cm, 5.43 cm, 29.76 cm2, and 23.25 cm, respectively. In contrast, the study properties under wind velocity of 3 m s-1 reached 12.41 cm, 7.06 cm, 46.90 cm2, and 29.96 cm, respectively. Similarly, under a wind velocity of 6 m s-1, the study characteristics increased to 13.07 cm, 9.08 cm, 60.10 cm2, and 32.46 cm. In addition, at a 12% slope, in no-wind and wind velocities of 3 and 6 m s-1, 16, 25, and 32 cracks of different dimensions were formed on the soil surface, respectively. Also, at a 30% slope, under similar conditions (no wind and two wind velocities, viz., 3 and 6 m s-1), the number of cracks was 29, 36, and 40, respectively, and cracks of different dimensions were observed. These results indicate a significant effect of wind velocity and slope on the formation of cracks on the soil surface. The findings showed that, under WDR conditions, as the slope increased, the dimensional characteristics of cracks increased significantly ($P<0.01$). On the other hand, increasing wind velocity also significantly ($P<0.01$) increased the dimensional characteristics at the soil surface. The results of this study emphasize that increasing the slope significantly alters the dimensional characteristics of cracks. In no-wind conditions, cracks were distributed across the entire plot surface, but as wind velocity increased, they were mainly located in the middle and upper parts of the plot. The results of this study can provide managers and executives with comprehensive information for modeling soil erosion processes and for watershed conservation and management.

**Keywords:** Conjunctive Erosion Processes, Ecosystem Sustainability, Topographic Feature, Upward, Soil Dynamics, Soil Stability.

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# Preferential spatial co-location of organic matter with identified mineral phases in intact soil microstructures

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## ABSTRACT

The stabilization of soil organic carbon is facilitated by the interaction of organic matter (OM) with mineral surfaces. Given that both soil organic matter and mineral phases are heterogeneously distributed within the soil matrix at the microscale, the question arises whether the mineral phases preferentially co-locate with organic matter or whether their spatial distributions are independent. Combining the identification of distinct mineral phases with spatial mapping of organic matter within soil microstructures offers insights into soil organic carbon storage mechanisms. Here, we provide a novel two-step unsupervised segmentation of soil microaggregates in conjunction with mineral References to identify distinct mineral phases in intact soil microstructures and quantify the relative spatially distribution of OM to determine preferential co-location of OM and specific mineral phases.

By conducting nanoscale secondary ion mass spectrometry (NanoSIMS) measurements at 30 µm, we acquired elemental distribution of 19 References minerals covering common soil minerals under O- RF plasma, and resin-embedded intact soil microaggregates incubated with 15N-enriched litter (8.203 atom% 15N) under dual Cs+ and O- RF plasma. By applying this machine-learning approach in conjunction of mineral-dominated region of soil microaggregates and mineral References, we were able to distinguish mineral phases, such as calcite, iron oxides, illite and montmorillonite, in soil microaggregates. Nearest neighboring distance analysis revealed a preferentially spatial allocation between pre-existing OM and both calcite and iron oxides. Newly formed OM was found co-located with pre-existing OM or in the pore space, supported by the network analysis adjacent to native OM and non-active framework silicates. These findings demonstrate that the heterogeneous OM spatial distribution is not in random patterns but spatially co-located with specific mineral phases within biogeochemically diverse soil microstructures. These preferential allocation of OM to mineral phases reflect distinct OM stabilization mechanisms, like pore dependency and allow us to evaluate whether mineral reactivity serves as a reliable proxy, providing direct microscale evidence for mineral-specific pathways in soil organic carbon dynamics.

**Keywords:** NanoSIMS, soil mineral identification, spatial co-location, soil organic matter

# Morphological Characterization and Mapping-Based Classification of Soils in Two Locations in Southwest Nigeria

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**ABSTRACT**

This study presents a comprehensive evaluation of soils and their agricultural potential in two locations in Southwest Nigeria, utilizing both morphological characterization and mapping-based classification. Soil samples were collected from various pedogenic horizons and analyzed for their physical and chemical properties. The soils were generally deep, ranging from sandy loam at the surface to sandy clay and clay in the lower horizons. The classification results revealed that the predominant soils in the study area are Alfisols, specifically classified as Ustalfs under the USDA Soil Taxonomy. The major soil types include Kanhaplustalfs, Paleustalfs, Kandiustalfs, and Haplustalfs, reflecting the presence of both argillic and kandic horizons. According to the World References Base classification, all pedons were identified as Lixisols, characterized by an argic B horizon with a cation exchange capacity (CEC) of less than 24 cmol (+)/kg clay and a base saturation of 50% or more. Notably, pedons varied into specific qualifiers such as Haplic and Ferric, particularly for those exhibiting Fe-Mn concretions. In Local Classification Series, soils were categorized within the Iwo Series and Ibadan Series, highlighting differences in texture and drainage properties. These findings revealed the diversity of soil types present, which is critical for informing effective agricultural management practices. Consequently, best management practices are recommended to enhance soil performance and sustain agricultural productivity across these regions.

**Keywords:** Alfisols, Characterization, Classification, Lixisols, Mapping, Morphology

# Identification of Key Factors for Soil Drainage Classification via Color Metric Comparison from Soil Images

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**ABSTRACT**

Drainage class is a critical factor in evaluating soil for crop suitability, water management, and sustainable agricultural planning. Traditional classification methods, which rely on field surveys and expert judgment, can be subjective. This study aims to establish objective criteria for soil drainage classification by analyzing color properties extracted from soil images. A total of 88 soil samples were collected from diverse parent materials and drainage classes. Soil colors were quantified using the Munsell soil color system, HSV, and CIELAB color spaces. In well drained and moderately well drained soils, matrix colors exhibited high chroma (≧3), while redoximorphic features showed low chroma (1–2), indicating strong oxidizing conditions. In contrast, poorly drained soils displayed grayish matrix colors with low chroma (≦2) and reddish mottles with high chroma (≧4), reflecting alternating redox conditions. Hue values in the HSV space and a* values in the CIELAB space were particularly effective in distinguishing drainage classes: well drained soils generally had higher Hue and a* values, whereas poorly drained soils tended toward lower Hue and negative a* values. Phyllite derived soils exhibited unique characteristics due to the inherent color of the parent material, highlighting the need for integrated interpretation. These findings demonstrate that digital image based soil color analysis, particularly using Hue and a* values, provides a quantitative and scalable approach to classifying soil drainage classes.

# Arbuscular mycorrhizal fungi hyphal density rather than diversity stimulates microbial necromass accumulation after long-term Robinia pseudoacacia plantations

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## ABSTRACT

Robinia pseudoacacia plantations are an effective strategy for preventing soil erosion, enhancing soil fertility, and stimulating carbon (C) sequestration in barren systems, supported by symbioses with arbuscular mycorrhizal (AM) fungi and rhizobia. However, the effects of AM fungal diversity and hyphal density on microbial necromass and SOC accumulation after long-term Robinia pseudoacacia plantations remain unclear. We hypothesize that increased AM fungal diversity and hyphal density after afforestation stimulate SOC formation by facilitating fungal and bacterial necromass C (FNC and BNC), glomalin (GRSP), and extracellular polymeric substances (EPS), with the contributions increasing as forest age. To test this hypothesis, microbial necromass, SOC, AM fungal diversity, and hyphal density were measured in surface soil (0–20 cm) and subsurface soil (20–40 cm) of Robinia pseudoacacia plantations aged 10, 15, 20, 35, and >50 years. Results showed that SOC accumulation was largely confined to surface soil, predominantly as mineral-associated organic C (MAOC). The content of FNC, GRSP, and EPS-polysaccharide in surface soil also increased with stand age, which is closely associated with MAOC. This emphasizes that long-term Robinia pseudoacacia plantations primarily stimulate C accumulation in surface soil, likely due to GRSP and EPS-polysaccharide aiding in the aggregation and protection of microbial necromass C. Although the AM fungal diversity in surface soil decreased with stand age, the hyphal density increased alongside root biomass. The increase in hyphal density could facilitate FNC and EPS formation, thereby contributing to the MAOC and SOC accumulation. In contrast, the content of SOC and microbial necromass C in subsurface soil showed an absence of differences or was reduced. Overall, this study reveals that microbial necromass and SOC accumulation after Robinia pseudoacacia plantations occur in surface soil, with AM fungal hyphal density and associated exudates, rather than AM fungal diversity, serving as key predictors.

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# Predicting the interaction of a coated moldboard plow and soil compared to the conventional one using adaptive neuro-fuzzy inference system (ANFIS)

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## ABSTRACT

**Background and purpose:** The biggest disadvantages of the moldboard plow are excessive soil turnover and moisture loss, severe damage to the structure, increased soil erosion, and the sticking of wet soil to it. In this regard, coating the surface of the plow can help the soil move more smoothly and overcome the mentioned problems to some extent. The purpose of this study is to measure and predict the required draft force and the amount of soil fragmentation by the coated moldboard plow compared to the conventional one using adaptive neuro-fuzzy inference system (ANFIS).

**Materials and methods:** The independent variables included the plow type (conventional and coated), forward speed (3, 4 and 5 km/h) and depth (25, 30 and 35 cm). The dependent variables included the required draft force and the mean weight diameter (MWD) of the soil particles. 3 replications for each condition and a total of 54 plots were considered. The draft force was measured by a three-point frame-type dynamometer and the MWD of the soil particles was measured using shaker and sieves. Data were analyzed in SPSS and significant interactions were extracted using Genstat. Field data was used to train ANFIS in MATLAB (2021) software.

**Findings:** The results showed that the effect of plow type, forward speed and depth on the required draft force and the MWD of soil particles was significant ($P<0.01$). Regarding the interaction effects, only the two-way interaction of forward speed on plow type on the MWD of soil particles was significant ($P<0.05$). The highest and lowest values of the MWD were 35 and 14.1 mm at speeds of 3 and 5 km/h, depths of 35 and 25 cm in the coated and conventional plow, respectively. The highest and lowest values of draft force were 649.44 and 409 kg at speeds of 5 and 3 km/h, depths of 35 and 25 cm in the conventional and coated plow, respectively. Regression models predicted the draft force with higher accuracy ($R2=0.9275$) than the MWD ($R2=0.8236$). ANFIS best model (gaussmf) also predicted the draft force with higher accuracy ($R2=0.9998$) than the MWD ($R2=0.9988$).

**Conclusion:** It is concluded that the soil tilled by the coated plow was less disturbed and its MWD was larger, this type of plow also requires less darft force and is effective in saving energy consumption. if farmers are forced to use a moldboard plow, using this type of plow helps to stabilize and protect the soil structure while reducing energy consumption. The ANFIS approach, with its outputs, including three-dimensional graphs was more accurate than regression.

**Key words:** Moldboard plow, MWD, draft force, chromium-nickel coating, ANFIS

# SEM–EDS and Micromorphological Evidence of Kaolinite–Hematite Interactions in Ferruginous Duricrusts from Devonian Sediments of the Parnaíba Basin (Central-North Brazil)

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**ABSTRACT**

Extensive flat and stepped surfaces in the state of Tocantins (central-north Brazil) host broad areas of ferruginous duricrusts (Petric and Pisoplinthic Plinthosols) that play a key role in preserving and shaping the landscape. In the central part of the state, where siltstones and sandstones ofthe Pimenteiras Formation (Devonian, Parnaíba Basin) crop out, these soils are closely associated with the Lajeado Range and the Tocantins Depression. Summit Petric Plinthosols are characterized by intense lateritization and cementation, whereas the Pisoplintic Plinthosols profiles located in the depression show a lower degree of weathering, containing abundant alteromorphic nodules.

Ferruginous ooid micronodules were identified in thin sections associated with alteromorphic nodules in Pisoplinthic Plinthosols from siltstones ofthe Devonian Pimenteiras Formation in the depression. Initially, these nodules were interpreted as related to the parent material or as possible microfossils. However, detailed micromorphological observations revealed a pedogenic origin. In contrast, ferruginous ooid micronodules were not identified in the Petric Plinthosols ofthe summit. Therefore, thin sections from both ferrugínous duricrusts in the Tocantins Depression and in the Lajeado Range were examined under optical microscopy, and selected areas of interest were subsequently analyzed by SEM–EDS in order to identify the main pedogenetic processes responsible for ooid formation and to understand why they do not occur in the summit profile.

We identified that ooid formation begins with the epigenetic replacement of kaolinite booklets by hematite through the process offerrolysis. The lamellar morphology, unstable for iron oxides, undergoes centripetal reorganization, giving rise to hematitic ooids. Conversely, in the intensely lateritized summit profiles, kaolinite and hematite coexist, forming kaolinitic nodules cemented by ferruginous flows. Environmental variation—particularly topography and pH—likely plays a fundamental role in determining the weathering rate and, consequently, the pedogenic processes and morphological features produced.

**Keywords:** ferruginous ooids; ferrolysis; Plinthosols; laterite

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# Segmentation-Guided Conditional Diffusion with Optical Flow Constraints for 3D Interpolative Super-Resolution of Soil CT ImagesZ

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## ABSTRACT

Soil pore structures at the microscale play a critical role in regulating water transport, gas diffusion, and biogeochemical carbon cycling processes. However, soil CT imaging inherently suffers from a trade-off between spatial resolution and scanning field of view, which often leads to insufficient resolution and structural discontinuity along the axial direction in three-dimensional CT volumes. These limitations significantly hinder accurate pore network reconstruction and multiscale soil process modeling. Conventional interpolation and super-resolution methods typically rely on local texture assumptions and struggle to preserve pore geometry and cross-slice continuity, frequently resulting in pseudo-pores and fragmented structures.

To address these challenges, this study proposes a segmentation-guided conditional diffusion framework with optical flow constraints for three-dimensional interpolative super-resolution of soil CT images. The proposed method integrates structural priors and spatiotemporal consistency constraints within a unified conditional diffusion paradigm to achieve physically consistent high-resolution reconstruction of soil pore structures. First, a soil-specific segmentation model is trained to extract robust pore probability maps from low-resolution CT slices, which are explicitly introduced as structural conditions into the diffusion denoising process. This guidance enables the model to focus on critical pore regions while suppressing non-physical texture generation. Second, to enhance inter-slice structural continuity, an optical flow–based constraint is incorporated to model correspondences between adjacent CT slices, effectively transforming the 3D interpolation problem into a temporally correlated conditional generation task. This design allows the diffusion model to capture pore morphology evolution and displacement along the axial direction. Furthermore, leveraging the strong distribution modeling capability of diffusion models, fine-scale pore structures are progressively restored through iterative denoising, mitigating structural distortion caused by one-step reconstruction strategies.

Extensive experiments were conducted on industrial soil CT datasets covering multiple soil types and scanning conditions. Quantitative results demonstrate that the proposed method consistently outperforms conventional interpolation techniques and existing 3D super-resolution models in terms of PSNR and SSIM. More importantly, evaluations based on pore-related physical indicators, including porosity, specific surface area, and pore connectivity, show high agreement between the reconstructed volumes and high-resolution References data. Qualitative visualizations further confirm that the proposed framework effectively recovers fine pore morphology while maintaining cross-slice structural coherence, significantly reducing pseudo-pore artifacts and axial discontinuities. In summary, the proposed segmentation- and flow-constrained conditional diffusion approach provides a robust and physically consistent solution for 3D interpolative super-resolution of soil CT images, offering reliable high-resolution structural data to support soil pore network modeling and carbon cycle research.

# Proto-soils of extreme environments: understanding chemical composition at a microscale with the use of Raman spectroscopy

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**ABSTRACT**

A large portion of land is covered by proto-soils formed in the absence of vascular plants with root systems. Such soil bodies are common in various extreme environments, e.g., ice-free areas of Antarctica, High Arctic, arid and high-mountain regions. They normally have shallow profiles shaped by various microbial biofilms / cryptogamic biocrusts and represent the best available real-time models to approximate initial stages of soil formation in the Precambrian. Nowadays, they support such basic functions common to full-scale soils as carbon and nitrogen cycling, organic matter stabilization, transformation of minerals, and others. Given the specific microstructure of proto-soils with microbial horizons, their study requires sensitive non-destructive methods that have high spatial resolution, e.g., Raman spectroscopy. Here, we focus on the properties and microscale chemical heterogeneity of proto-soils with endolithic / hypolithic cyanobacteria-dominated microhorizons from East Antarctica and proto-soils under cryptogamic biocrusts from proglacial settings of High Arctic, all studied with the use of Raman microspectroscopy. The presentation is based on (1) single-spectrum Raman data obtained from point measurements of intact samples as well as on (2) hyperspectral Raman data analysis (chemometrics) and chemical maps obtained from thin sections with the spatial resolution of several microns. We revealed high spatial heterogeneity and redistribution of various components along proto-soil profiles. For proto-soils on non-carbonate rocks (gneisses, East Antarctica), a continuum of different calcium carbonate phases, including such polymorphs as calcite and aragonite, has been identified. It is likely that in situ weathering of Ca-containing silicate minerals contributed to the formation of CaCO3 here. In all proto-soils of East Antarctica and the High Arctic, Raman spectra contained bands of polyenes with heterogenous molecular structure, mainly various carotenoids. Raman bands of polyaromatic C, calcium oxalates (whewellite and weddellite), and Fe oxide-hydroxides (mainly hematite and goethite) were also common. Combinations of bands characteristic of Fe oxide-hydroxides and carotenoids, as well as of CaCO3 and carotenoids obtained from a volume of around 1 cubic micron, suggested spatially localized associations of these compounds. Overall, with the use of Raman microspectroscopy, we show that shallow profiles of proto-soils do not necessarily imply simplicity but instead may have very complex microscale patterns. Along with primitive profiles that have a single organogenic horizon of microbial and/or cryptogamic origin, they may also exhibit complex associations of paragenetic horizons and even profiles with eluvial-illuvial differentiation.

**Acknowledgments**

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# IUSS Digital Soil Thin Section Collections Working Group

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**ABSTRACT**

Drawing from discussions during the 17th International Conference on Soil Micromorphology, held in Puno, Peru, in 2024, the IUSS Executive Committee approved the establishment of the 'Digital Soil Thin Section Collections' Working Group, within Division 1 'Soils in Space and Time', in 2025. The goal of this Working Group is the establishment of an international framework for the digitization, characterization, archiving and sharing of soil thin sections collections. Several objectives have been identified, including: 1) Establish and maintain an international registry of soil thin section collections; 2) Develop soil thin section digitization technologies and techniques; 3) Establish international standards and guidelines for soil thin section digitization; 4) Digitize legacy characterizations and interpretations of soil thin section collections, as well as other associated data; 5) Establish open-access digital repositories (FAIR) of soil thin sections collections; 6) Develop AI-assisted techniques for advanced characterization of soil thin section collection imagery; and 7) Develop AI-assisted techniques for text mining of legacy documentation and data related to soil thin section collections. This presentation will provide an update on the development of the Working Group, as well as an opportunity to present and discuss plans for subsequent activities aimed at engaging the broader stakeholder community.

# Soil Profile Characteristics and Vertical Stratification Beneath Nabkhas in the Coastal Deserts of Oman

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**ABSTRACT**

Nabkhas are aeolian sand accumulations formed around desert vegetation and represent distinct pedological units within arid landscapes. This study examines the soil profile characteristics and vertical stratification of Nabkhas in Oman's coastal regions, with a focus on texture, moisture distribution, salinity, and dynamics of organic matter. Soil samples were collected from Nabkha bodies and adjacent interdunal areas and analyzed for moisture content, organic matter (OM), $pH_e$, electrical conductivity ($EC_e$), and selected soluble ions ($NO_3^-$, $Ca^{2+}$, $K^+$, and $Na^+$). Detailed vertical soil profiles were examined to assess textural layering and its influence on water retention and salt accumulation.

The results revealed pronounced vertical stratification beneath Nabkhas, characterized by coarse sandy surface layers overlying finer-textured loamy horizons at depths of approximately 60–150 cm. These fine-textured layers functioned as capillary barriers, significantly enhancing subsoil moisture retention (20.1–57.7%) compared to the overlying coarse sands (2.9–7.2%). Electrical conductivity increased with depth, indicating the accumulation of salt in lower horizons. Organic matter content was markedly higher beneath Nabkhas (up to 6.15%) than in surrounding interdunal soils (approximately 1.08%), reflecting enhanced pedogenic development. Despite these vertical contrasts, surface soil properties showed minimal differences between Nabkha and interdunal environments.

Overall, Nabkhas promotes the development of vertically differentiated soil profiles that enhance moisture storage and influence salinity distribution in arid coastal systems. These findings highlight the pedological significance of Nabkhas as localized zones of improved soil functionality within desert environments.

**Keywords:** Nabkhas; Desert vegetation; arid pedogenesis; subsurface moisture

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# Micropedology and Artificial Intelligence – evolution of quantitative approachs

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**ABSTRACT**

Micromorphological analysis of soil thin sections has traditionally been regarded as a qualitative or semiquantitative approach, while the global scientific community is advancing towards automated measurements and generation of large, high- quality datasets. Conventional micropedology studies primarily focus on features of the soil solid phase-–such as soil structure, solid mineral formations, mineral weathering, and coatings. However, many published soil descriptions remain incomplete, as researchers often emphasize only the features most relevant to their specific study objectives (Stoops et al., 2018). As a result, the full analytical potential of existing thin sections is frequently underutilized even though these samples remain preserved in institutional or personal collections and often represent soil profiles that are no longer accessible for field sampling. While there is great interest in conducting quantitative micromorphological studies, existing licensed software (e.g., ImagePro) is expensive and open-source tools (e.g., ImageJ) are very limited and/or require strong programming skills. Some previous work has applied Geographic Information System (GIS)-based solutions (Gutiérrez Castorena et al., 2018; Torres-Guerrero et al., 2023), but it also requires specialized skills in GIS analysis. To aid image analysis, some researchers apply pigments to soil samples as thin sections are being made, but these pigments may alter other soil properties in the thin sections. As such, all these existing methods are time-consuming and require either manual work or strong computational skills. The proliferation of Artificial Intelligence (AI) techniques may offer a solution, with computer vision leading to rapid advancements in image analysis across scientific disciplines. Greater computational resources, coupled with a growing number of open-source AI tools, are democratizing advanced image analysis, allowing users with little-to-no coding experience to use AI in their research. Here, we present one such example–a new open-source AI tool designed to quantify soil porosity in thin section imagery in a rapid and reproducible way–that will significantly reduce the time needed to perform, and eliminate existing barriers to, quantitative micropedology.

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# Monitoring spatial changes in soil organic carbon in response to land-use and slope direction

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## ABSTRACT

Soil organic carbon (SOC) plays a fundamental role as one of the key and important components in soil health and ecosystem stability (Liang et al., 2025). SOC improves soil quality and reduces erosion by increasing water holding capacity and improving physical and chemical properties (Murphy, 2015; Page et al., 2020; Bai et al., 2025). SOC can also act as a carbon sink and prevent the release of carbon dioxide into the atmosphere and the increase in greenhouse gases (Lal, 2003; Mgalula et al., 2021). The presence of SOC can help create suitable habitats for microorganisms and other living organisms and increase biodiversity (Philippot et al., 2024). On the other hand, it can affect aspects of the economy and agriculture by increasing crop production and reducing the need for chemical fertilizers (Kamakaula, 2024). Some factors, including land-use changes (such as agriculture, deforestation, and urban development), climatic conditions (the role of temperature and precipitation on the decomposition of organic matter), and soil management (use of organic fertilizers) affect changes in SOC. The spatial distribution of SOC and the understanding of the factors affecting it are essential for better management of soil resources (Guo et al., 2025). Understanding the distribution of SOC has helped to provide a clear understanding of the biological and chemical processes of the soil, and to determine their effects on soil quality and ecosystem stability (Stanley et al., 2024). Among the factors affecting SOC are changes in land-use and slope direction. Land-use, such as the conversion of forests to cropland, can lead to a decrease in SOC, while appropriate management can help increase it. Also, slope direction has a great impact on the erosion and accumulation of SOC; the erosion rate is usually high on steep slopes. Therefore, by identifying and protecting sensitive areas and adopting appropriate strategies, soil quality can be maintained, ecosystem function and agricultural production can be improved. The present study aimed to investigate the effects of land-use and slope direction on SOC distribution in the Sari watershed, Mazandaran province, northern IRAN. This region, with its diverse vegetation cover and temperate and humid climatic conditions, is considered a suitable example for analyzing spatial patterns of SOC in foothill and plain areas. Three main data sources were used to conduct the present study. First, Sentinel-2A images with a spatial resolution of 10 m were used to produce a land-use map. The land-use categories included barren and sparse lands, urban areas, rainfed and irrigated agricultural lands, rangeland, and tree cover. Second, a SRTM digital elevation model (DEM) with a resolution of 30 m was used to extract the slope direction layer; the directions in this study were divided into four main groups: North, East, South, and West. Third, a global soil map (soil grids) with a resolution of 250 m from the ISRIC database was used to extract the percentage of SOC at surface depth. Data processing included aligning the layers to a single image system (corresponding UTM Zone) and creating an overlap between pixels to allow extraction of SOC values for each land-use category and slope direction. SOC was then categorized into five qualitative categories: very low, low, moderate, high, and very high based on the statistical distribution of values in the area. This categorization allows for a more detailed analysis of the relationship between land-use, slope direction, and SOC distribution. Analysis of the distribution of land-use areas in geographical directions showed that rainfed lands and tree cover have the largest share of area in the North (24.71% and 47.79%) and South (39.66% and 36.70%). While irrigated agricultural showed their largest share in the West (15.25%). Urban areas and barren and sparse lands had a smaller share in all directions, and the distribution of rangeland was also relatively uniform. These results indicate that the spatial distribution of land-uses is affected by slope and environmental factors and can play an important role in SOC accumulation in combination with geographical directions. Analysis of SOC in different land-uses showed that the highest share of soil with very low SOC was in barren and sparse lands (60.52%) and rangeland (57.76%). While tree cover and irrigated agricultural had the highest share in moderate to high categories. This pattern indicates the direct effect of vegetation cover and agricultural management on soil carbon accumulation. So that tree cover recorded the highest amounts of SOC with 28.17% in the high and 9.93% in the very high category, and irrigated agricultural also had high amounts of SOC with 32.26% in the moderate and 21.58% in the high category. Analysis of the effect of slope direction also showed different patterns. The South direction had the highest share of soil with low SOC (very low: 41.6% and low: 35.5%), while the North and East directions had higher values in the moderate and high categories. The West direction also showed a relatively balanced distribution of SOC in the moderate and high categories. These results emphasize that climatic factors such as solar radiation, temperature, and soil moisture in different directions play an important role in maintaining and increasing SOC. The combination of land-use analysis and slope direction showed that the spatial distribution of SOC was influenced by the interaction of these two factors. In particular, tree cover and irrigated agricultural were identified as areas of high SOC accumulation. While barren and rainfed in the South direction were the areas with the lowest SOC. These findings indicate that maintaining vegetation cover and applying appropriate management methods in agriculture can effectively increase soil SOC and be effective in reducing soil erosion and improving soil quality. Correlation analysis showed that there was a strong positive relationship between land-use type and SOC; tree cover had the highest positive correlation with high and very high SOC categories ($r \approx 0.68$) and irrigated farmland showed a moderate to high correlation ($r \approx 0.59$) with high SOC. In contrast, barren and rainfed lands had a significant negative correlation with high SOC ($r \approx -0.61$). On the other hand, slope direction also had a significant effect on SOC; North direction had a positive correlation with moderate and high SOC ($r \approx 0.57$), East direction had a moderate positive correlation ($r \approx 0.49$), and South direction had a significant negative correlation with low SOC ($r \approx -0.64$). The findings of the present study provide a comprehensive framework for spatial analysis of SOC based on land-use and slope direction and can be used as a basis for scientific decision-making for soil resource management and sustainable agricultural development in the study area. This region is located in Northern Iran and on the Caspian Sea coastline, and with its temperate and humid climate characteristics and diverse vegetation cover, it is considered an exemplary case for investigating the interactions between natural and human factors on soil health and carbon accumulation. The results of this study can help develop SOC management strategies, protect natural resources, and mitigate the negative effects of climate change in similar regions.

# Integrating Micro- and Submicromorphological Data for Diagnosing Redoximorphic Conditions in Soils of Topographic Depressions in the Oka-Don Lowland

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**ABSTRACT**

Defining soil water regimes-the interaction between saturation and redox conditions-remains challenging. Direct monitoring is constrained by resource-intensive long-term networks, necessitating robust indirect methodologies. Redoximorphic features provide valuable hydrological archives through their response to redox shifts. Comprehensive analysis of these features, supported by nodule elemental data and micromorphology, enables detailed characterization of water regimes and drainage patterns.

Our study employs an integrated macro-, micro- and submicro-morphological approach examining: i) the morphology, boundary sharpness, and elemental composition of redoximorphic features; ii) the thickness and material composition of illuvial clay features; and iii) the decomposition degree and spatial organization of organic matter.

We posit that macromorphological analysis provides initial diagnostics, micromorphology reveals pedogenesis, and SEM-EDS provides precise compositional data. This integrated approach develops criteria for hydrological reconstruction and tests micromorphological indicator reliability.

Applying this methodology to soils from nine depressions in the southern Oka-Don Lowland enabled us to delineate the hydrological regimes of three soil groups: Oxygleyic Gleysols (Clayic, Histic), Albic Mollic Gleyic Stagnosols (Clayic), and Albic Mollic Histic Planosols (Clayic).

Soils subject to prolonged groundwater saturation (Gleysols) are characterized by diffuse Fe-nodules, a general absence of clay coatings, abundant fresh and charred organic residues, and amorphous organic punctuations within the groundmass. In contrast, soils experiencing periodic, shorter-term waterlogging (Stagnosols and Planosols) exhibit sharply bounded, Mn-enriched redoximorphic features, well-developed clay and organo-clay illuvial coatings, a dominance of partially and fully decomposed organic matter, and a more integrated distribution of humus into groundmass. The nodule composition in Planosols contains more Mn than in Stagnosols, indicating more prolonged waterlogging in the latter.

The integrated analysis establishes that Gleysols develop under permanent saturation from both surface and groundwater sources, Stagnosols under periodic surface waterlogging with intermittent groundwater influence, and Planosols under solely surface saturation. This gradient reflects decreasing waterlogging duration Gleysols-Stagnosols-Planosols and shows how micromorphological signatures effectively characterize hydrological regimes.

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# Final stage of loess accumulation in the periglacial zone of the Northern Caspian region.

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**ABSTRACT**

In the Northern Caspian region, the final stage of Late Pleistocene loess accumulation was linked to transgressions and regressions of the Khvalynian Sea, which altered the composition and structure of parent materials. The maximum transgression boundary (48-50 m) extended to the foot of the Obshchy Syrt and the ridges of the Syrt Trans-Volga region. As the sea retreated, loesses accumulated on the exposed areas, and landscapes typical of the semi-desert zone in the southeastern Russian Plain began to form.

The most specific parent materials for soil formation in the Northern Caspian are the Lower Khvalynian chocolate clays (CC), whose maximum thicknesses are confined to the II terraces of the Volga and Ural rivers. Recent syntheses (Svitoch, 2015) on the properties, geography and occurrence patterns of these specific clays have shown that CC represent a complex litho-facial formation with layered texture and are not typical for the Volga-Ural interfluve area. Current dating of References sections in the Lower Volga region indicates that their accumulation occurred after the Last Glacial Maximum (17-13.1 kya). The highest accumulation rates of CC corresponded to the Bolling-Allerod period (14.7-13.2 kya, sea level 20-22 m). After 12.5 kya, the Yenotayevka regression developed (Kurbanov, 2020). On the interfluve surfaces (26-28 m a.s.l.) in the Dzhanybek endorheic plain, OSL dating was conducted on layers containing shells and CC fragments at depths of 60-90 cm in modern soils of dry-steppe solonetzic complexes. These studies (dating, micromorphology and minerology) revealed that the investigated CC and the upper loess layer, in which modern soils of the dry-steppe solonetzic complexes in the northern part of the Caspian Lowland have formed, entirely fall within the stratigraphic interval of the Lower Khvalynian deposits - they accumulated during the maximum Khvalynian transgression. The upper loess layer's distribution confirms final Late Glacial accumulation in the Northern Caspian periglacial zone. Our dates show loess formed during Ostashkov Glaciation decay under arid, cold conditions, causing fracturing, gypsum content, and cryogenic aggregation in CC layers and soil horizons. The thin loess layer shaped Holocene soils' lithology and with relict cryogenic features, explains the region's soil complexity.

**Acknowledgments**

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# The Micromorphology of Brazilian Oxisols (Latossolos): variability and fertility connections of the most representative agricultural soil in the tropics

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**ABSTRACT**

The Brazilian Oxisols (Latossolos, Ferralsols) are well-drained deep soils, weathered and, nutrient-poor, with a basic oxidic/kaolinitic mineralogy of low CEC and severe leaching. Despite the occurrence in all Brazilian territory, little is known about the variability of micromorphological characteristics of Oxisols across the country. We hypothesize that the Brazilian Oxisols present a considerable micropedologocal variability that is regionally manifested and traced according to the environmental characteristics of different Brazilian biomes. In this way, we compared the whole suite of Oxisols across the country (Latossolos Amarelos, Latossolos Vermelho-Amarelos and Latossolos Vermelhos) from Brazilian biomes, using robust legacy data produced by published soil surveys. The Red Oxisols (Latossolos Vermelhos) represent the suborder with the greatest degree of microstructural development and weathering, the highest contents of Fe and Al oxyhydroxides, clayey texture, greatest microaggregate roundness, pH and base saturation. Conversely, the Yellow Oxisols (Latossolos Amarelos) showed welded, coalesced microaggregates, combined with the highest contents of kaolinite, silt, sand. The Red-Yellow Oxisols (Latossolos Vermelho-Amarelos), in turn, presented intermediate characteristics, confirming that soil color is a key attribute for differentiating the microstructural development of Oxisols (Latossolos), regardless of the biome. The uniformity of chemical and mineralogical composition of the micromass at micraggregate scale reveals the long-term pedobioturbation for creating stable, minute aggregates of similar composition, despite the varying presence of silt-sized particles of Charcoal, quartz and Ti-bearing minerals. The importance of micropedology for fertility aspects, like P adsorption, is discussed.

# Stepped Canal and Levigation Pools in Teotihuacan, a study through their micromorphological and hydraulic relationships

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**ABSTRACT**

Much of the city of Teotihuacan, including its everyday life and rituals, reflected the devotion and reverence of its inhabitants for water, as seen in murals, paintings, and ceramics. However, the discovery of a stepped canal, built during the Patlachique phase (200 BC–0 AD) and subsequently sealed during the Miccaotli phase (150–200 AD), provides an opportunity to document the Teotihuacans' earliest hydraulic works in detail. This research aims to analyse the micromorphological relationships among the different processes, sediments, and types of fills, as well as their relationships with hydraulic works. The 356-metre-long canal, which is 3.7 metres wide at the base and 1.4 metres deep, has four steps facing north and was discovered in 2002. It was explored through twelve test pits between 2003 and 2004. It is located north of the Citadel, running parallel to the San Juan River and perpendicular to the Calzada de los Muertos. Altered and unaltered samples were collected from each stratum or layer of the fill for laboratory analysis and thin sections. The results indicate that the stepped canal has all the necessary hydraulic characteristics to transport water. However, its location and design suggest that the water originated from the Calzada de los Muertos, rather than from the east as initially presumed. The presence of two spillways to the west of the structure and alluvial sediments whose thickness decreases towards the east provide evidence for the direction of runoff. Additionally, the presence of sediments comprising soil aggregates with an undifferentiated structure, followed by rounded tepetate particles (tuffs), indicates soil erosion and the exposure of the underlying material. This also demonstrates that the Calzada de los Muertos was not paved. The channel had traces of different fine sediments on its margins, indicating dredging down to the tepetate. A homogeneous layer of fine material, 10–25 cm thick, was identified on the tepetate, completely covering the channel base. This layer contains cavities and aggregates of various types, some of which have diatoms distributed randomly throughout. These features are characteristic of a process of selective extraction and filling, which probably served as a waterproofing agent. This filling was buried under a sequence of sediments with very fine laminations, composed of sands and silts with a banded distribution but no oriented clays, indicating that no clays were in suspension after the spill. These colloids were likely artificially separated and used to produce other items, such as ceramic artefacts, structural fillings, and adobe bricks. Accumulations of carbonised remains with calcareous ashes at the beginning of the canal suggest that rituals were performed there. In contrast, the parallel distribution of remains after the spillways indicates that rituals were not performed there. Finally, the hydraulic system was closed using materials from a new project that formed the San Juan River and crossed the city.

**Keywords:** fillings, sediments, spillway, erosion.

# Micromorphological Insights into Intra-Urban Spatial Dynamics: A Case Study from Oudenaarde (Belgium)

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**ABSTRACT**

The diversity of anthropogenic soils in urban environments reflects shifts in land use and spatial organization, providing essential insights into human–environment interactions and stages of urbanization. A notable example is the widespread 'Dark Earth' (DE), a macroscopically homogeneous deposit that contains diverse micro-stratigraphic features, reflecting complex formation processes. This study employs soil micromorphology to examine how DE documents intra-urban soil variability and spatial dynamics within a historical context.

We analyzed DE from two sites in the historical center of Oudenaarde: one at the edge of town, next to a former canal (Broodstraat) and another at the central marketplace. A multi-proxy micromorphological approach was applied, incorporating analyses of soil organic matter, bone fragments, phytoliths, coprolites, and intestinal parasite eggs. Current results demonstrate that both natural and anthropogenic processes have contributed to the formation of both sites. The Broodstraat site reveals a predominance of natural processes, indicative of an urban wasteland near the Scheldt river. Ongoing analysis of the marketplace DE shows greater soil homogenization and intense reworking, suggesting frequent disturbances and managed urban use.

Overall, this comparative study highlights the value of soil micromorphology in decoding urban stratification and demonstrates how seemingly uniform anthropogenic soils in urban context can shed light on spatial dynamics and human–environment interactions in historical urban landscapes.

# Long-term nitrogen fertilization effects on soil mineralogy and micromorphology: The Magruder Plots

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**ABSTRACT**

Mineral weathering is heavily influenced by the soil forming factors including climate, topography, parent material, and biota, and humans have become a part of this process as well. The focus of this experiment is to explore the relationships between agriculture and soil weathering processes, specifically the relationship between soil minerals and long-term fertilization. Organic acids and other root exudate materials in soil environments play a role in the dissolution and transformation of soil minerals. Microbially facilitated denitrification reaction results in a net release of H+ and the application of nitrogen fertilizers can affect soil mineralogy as well, specifically increasing the amount of NH4+ fixed by 2:1 minerals and even in a relatively short timescale (Matocha et al., 2016; Bajwa, 1982). Evidence suggests that agricultural activity and inputs are changing soil properties that were previously understood to be inherent, like mineralogy and soil texture. Long-term experiments and soil archives provide unique opportunities to assess how soils change over time in response to land management. One long-term fertility experiment in the Great Plains region is the Magruder plots outside of Stillwater, OK, established in 1892. After over a century of cultivating continuous wheat, grain is still harvested from the zero-input check plot. These plots are iconic for the region as one of the oldest long-term experiments and the oldest continuous wheat trial in the country. However, there are no published mineralogical assessments on the plots to investigate potential changes driven by continuous tillage and nutrient amendments. There is a unique and interesting opportunity in these plots to further develop a whole-picture understanding of the relationship between soil minerals and agricultural management. Clay mineralogy and a suite of soil chemical measurements were completed, as well as macro- and micromorphological descriptions and the results will be discussed.

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# Quaternary landscape dynamics of the Venetian Pre-Alps (NE Italy) revealed through paleosols micromorphology

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## ABSTRACT

Micromorphological examination of paleosols can be one of the most useful tools to reveal the pedogenic process that occurred in situ, from the original unweathered parent material to the current soil. In addition, paleosols record the local response to more global climatic and environmental changes especially over the Quaternary glacial and interglacial phases (Scarciglia et al., 2023). Pedogenesis, on a microscopical level, entails the weathering of primary minerals and rock fragments, resulting in the formation of secondary minerals and pedofeatures that provide key insights into the environmental conditions prevailing during their formation. In this light, soil micromorphology represents the well-known concept of "pedomemory" (sensu Targulian and Goryachkin, 2004), which is basically the soil capability of maintaining memory of the complex climatic and environmental settings of soil formation especially within micromorphological features. During the last decades micromorphology has been deeplyused to properly validate with a microscopic approach the existent classification of soils and to define differences among soil types (Wilding et al., 1985). Doing so, the most developed soils, like Ultisols usually found on the Pleistocene stable surfaces (Soil Tax, 1999), have been microscopically characterized mostly by the identification of illuviated clay and iron-bearing pedofeatures (Fedoroff & Eswaran, 1985; Cremaschi, 1987). Micromorphological description of paleosols is the key instrument to detect variability along a single profile and among different paleosols, which generally tend to exhibit similar macroscopic and chemical characteristics due to their high level of alteration (Birkeland, 1975). That approach even provides valuable insights into soil genesis and its evolution over time. Thus, the integration of macroscale characterization and chemical-mineralogical data - coming from the analysis on bulk samples - with the micromorphological observation is the starting point for a complete study of paleosols and it is regarded as an optimal strategy for the comparative study of paleosols (Fedoroff and Goldberg, 1982). Micromorphology is mainly a qualitative approach. With the aim of acquiring quantitative, statistically-sound micromorphological data, that may support comparisons within and among soil profiles, our study further tests the determination of the Representative Elementary Area (REA) (Vandenbyygart and Protz., 1999) for each microfeatures of interest (e.g. clay coatings, iron nodules, porosity, etc.), through image analysis of thin sections.

In the context of the research, micromorphology is applied to enhance the knowledge of paleosols in the southern-eastern Italian Pre-Alps, where Last Glacial Maximum deposits are well-detectable and older, strongly weathered glacial and glaciofluvial deposits are scattered along the current valleys of the Piave and Soligo rivers (Carton et al, 2009). In detail, two soil profiles (M25/01 and M25/02) approximately 9 meters in depth were excavated and sampled using Kubiena boxes or extracting blocks of oriented undisturbed soil. They both pertain to glaciofluvial terraces, likely pertaining to the Middle Pleistocene, located at a distance of ca. 17 km within the Venetian foothills (figure 1). M25/01 profile comes from the second order of fluvial terraces developed on the creeping anticline of the Montello Hill, shaped during the Quaternary by the combined action of the fluvial erosion by the antecedent Piave river and the simultaneous continuous tectonic uplift (Picotti et al, 2022). M25/02 profile pertains to the soil developed on the highest glaciofluvial terrace within the Soligo valley originated by the deposition of glaciofluvial sediments from the Piave glacier outwash system.




**Figure 1:** overview of the study area showing the position of soil profiles (red dots) and the stable geomorphic surfaces on which soil is developed (yellow polygons).

From a mesoscopic point of view, both soil profiles comprise a strongly weathered buried stony pedostratigraphic level overlain by loess deposit; they mainly differ in the mineralogical assemblages of the conglomeratic parent material, which is more carbonatic in M25/02 soil profile. Given the similarities of soil macroscopic features, micromorphological comparative study is needed to better characterize the two soil profiles and then reconstruct the past paleoclimate and paleoenvironmental conditions, taking to the formation of such developed soils. This approach allows us to cast light on the dynamics of the Pleistocene-Holocene landscape evolution and support the geomorphic-stratigraphic correlation of landforms and deposits across the study area.

# Medieval Urban Cultural Layers in Contrasting Arid and Humid Waterlogged Environments: Morphological and Chemical Properties, and Genesis

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**ABSTRACT**

Cultural layers are soil-sedimentary deposits formed through complex interactions of simultaneous and successive anthropogenic and natural processes. Despite extensive research on archaeological urban deposits, the role of environmental conditions in shaping the characteristics and properties of cultural layers remains poorly understood.

This study presents a comparative analysis of more than 8 m-thick medieval urban cultural layers – Urbic Technosols (Archaic) – at two archaeological sites situated in markedly different environmental conditions: Veliky Novgorod (Dfb warm-summer humid continental climate according to the Köppen climate classification; flat topography; waterlogged conditions) and the Dzhankent fortified settlement in the Aral Sea region (BWk cold desert climate; paleodelta setting; groundwater influence at the bottom of the section). The research is based on an integrated approach combining macromorphological, micromorphological, and physicochemical analyses.

The results demonstrate that at both sites, the formation of cultural layers was dominated by intensive anthropogenic inputs and the accumulation of highly variable organic, mineral, and pyrogenic materials related to construction and domestic activities. However, the subsequent geochemical preservation of archaeological materials differs substantially and is primarily controlled by zonal hydrological and climatic conditions.

In the cultural layers of Veliky Novgorod, formed under persistently waterlogged, reducing conditions, processes and features of gleization, redox-driven migration of iron and manganese, clay illuviation, and phosphate segregation prevail. These conditions strongly suppress biological decomposition and promote exceptional preservation of organic matter, including anatomically preserved wooden and grassy plant remains, with total organic carbon contents reaching up to 39%.

In contrast, at the Dzhankent site, transformation processes are governed by an evaporative water regime, high alkalinity, and salinity. Dominant processes include humification and mineralization of organic matter, as well as intensive accumulation of easily soluble salts, gypsum, and carbonates. Despite suppressed biological activity, organic remains undergo pronounced abiotic degradation and are partially stabilized through mineral encrustation by carbonates and soluble salts, resulting in low organic carbon contents (0.4–3.1%).

The study demonstrates that even under comparable anthropogenic pressures, the direction and intensity of soil-forming processes and the degree of preservation of cultural layers are primarily determined by environmental conditions. Urban cultural layers thus function as long-term archives reflecting human–environment interactions under contrasting climatic regimes.

**Acknowledgments**

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# Formation and Evolution of Volcanic Soils in Central Apennine Mountains (Molise, Italy)

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**ABSTRACT**

This study presents a pedological investigation of volcanic soils from central Apennine (Italy) and focus in a pasture area of notable ecological and cultural interest (1000 hectares), along historic transhumance routes (tratturi), now recognized as UNESCO Intangible Cultural Heritage. Four soil profiles were sampled along an altitudinal transect (1290-1360 m a.s.l.) made by the profiles: SM, CF, AS1 and AS2. SM is characterized by extremely dark brown topsoils with very high total organic carbon (TOC) content, reaching up to 77 g/kg. The topsoil overlies clay rich mineral horizons, likely developed from the Neapolitan Yellow Tuff (NYT) eruptive event. CF exhibits a thin topsoil resting on a "stone line" composed of siliceous gravel shaped by cryoclastic weathering. Below the discontinuity, the horizons show marked variations for structure and clay content. AS1 is characterised by shallow lithic contact and abundant glacial gravel derived from local denudation processes. In contrast, AS2 exhibits deep, lighter-coloured horizons enriched in manganese and iron concretions, together with a vertical sequence of buried BC horizons. Laminated pyroclastic layers (100-200 cm) in AS2 suggest episodic water stagnation and lacustrine sedimentation. Fepy/Feox (py/ox) ratios are low (0.1-0.2), and Alpy/Alox is 0.4-0.5 in surface horizons, increasing with depth, indicating vertical shifts in Al speciation (allophane/imogolite/Al-humus complexes); buried AS2 horizons reach Alpy/Alox > 1. Following WRB 2022, the profiles classify as (Aluandic) Andosols where andic properties are met (BD ≤ 0.9 kg dm−3, Alox+½Feox ≥ 2%, P retention ≥ 85%) and Siox < 0.6% in andic layers within 100 cm (≥15 cm cumulative). SEM-EDS shows elongated, highly vacuolar glassy fragments consistent with phytolith/opal-A (amorphous Si) from silicified grass tissues. The SEM images also reveal sub-spherical Mn-rich nodules with a distinctly concentric, laminated internal structure and massive outer rind, typical of pedogenic Mn-Fe nodules formed under fluctuating redox conditions. This layering indicates dissolution-reprecipitation cycles of Mn and Fe within the matrix, with Si and Al more diffusely distributed, implying that Mn-Fe oxides/hydroxides constitute the main sorbent phases against a silicate background. The combined effects of carbonate bedrock, distal volcanic inputs, karst geomorphology and mountain climate generate andic, organic-rich soils with intense Fe-Mn dynamics. These volcanic mountain soils underpin a wide array of essential ecosystem services, carbon sequestration, water and nutrient retention, pasture productivity, biodiversity and landscape stability. At the same time, they offer valuable References data for refining WRB soil classification and for guiding conservation-oriented management strategies within the Apennine pasture systems in central Italy.

# Micromorphological mechanisms reveal 45-year Anthropogenic barrier layer formation in Northeast China's Black Soil Region: pore connectivity collapse drives sustainable management imperative

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**ABSTRACT**

The Northeast China Black Soil Region, a vital global grain production zone, is experiencing severe degradation of its fertile Brown soils (Luvisols) due to intensive agricultural use. This study investigates micro-morphological mechanisms behind degradation of Brown soil (Luvisols) in Northeast China by comparing undisturbed forest soil with adjacent soil under 45 years of dry farming. Combined thin-section and physico-chemical analyses show the profile evolved from Ah-AB-Bt-C to Ap1-Ap2-AB-Bt-C, forming a plow pan. Significant changes occurred: pH, organic matter, and total nitrogen decreased by 2.72%, 13.46%, and 9.79%, respectively, while bulk density, available phosphorus, and available potassium increased by 2.26%, 30.25%, and 14.97%. Micro-morphology revealed a lower coarse/fine particle ratio,higher circularity. The plow pan (Ap2) porosity decreased, while the argic horizon (Bt) porosity increased. Voids shifted from connected planar types to isolated vesicular vughs, and illuvial clay changed from large masses to thin coatings. The understanding for silica-neoformation pathways were also improved. These findings provide micro-morphological evidence of anthropogenic degradation and a framework for sustainable soil management in this critical agricultural region.

**Acknowledgments**

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# Micro-scale pedogenic features in cold volcanic soils of Iceland: evidence from thin sections and SEM-based microanalysis

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**ABSTRACT**

Cold volcanic landscapes of Iceland host young, ash-influenced soils where pedogenesis proceeds under low temperatures, episodic wetting and strong parent-material control, often while volcanic inputs and physical reworking continue. This study investigates micro-scale pedogenic features in such soils by integrating thin-section micromorphology with scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM–EDS) and wavelength-dispersive spectroscopy (WDS). Thin sections from representative horizons were described using standard micromorphological criteria, with emphasis on groundmass organisation, microfabric, porosity and pedofeatures. Targeted SEM–EDS imaging and WDS spot analyses were used to characterise alteration rims on glassy particles and primary minerals, and to assess elemental redistribution linked to early weathering and short-range-order secondary products. Micromorphology reveals heterogeneous alteration of volcanic glass, ranging from fresh shards to particles with well-defined reaction fronts, alongside early microaggregate development. Pedofeatures include localised pore infillings and coatings around mineral surfaces, indicating microenvironments of enhanced moisture and solute availability. Microanalytical results show chemical differentiation at grain–matrix interfaces, consistent with incipient formation of secondary Al– Fe–Si phases and iron-rich coatings, as well as local concentration gradients suggestive of limited translocation at very short distances. The close juxtaposition of unaltered and altered materials within single thin sections suggests that early pedogenesis is spatially discontinuous, controlled by microscale variations in parent material texture, porosity and short-range hydrological pathways. By combining micromorphology with SEM-based microanalysis, this study provides process-based evidence for the initial stages of soil formation in cold volcanic environments and clarifies how pedogenic signals emerge within volcanogenic parent materials. The findings contribute to conceptual models of soil genesis in Icelandic landscapes and offer micro-scale constraints relevant to the classification and interpretation of young volcanic soils across cold-region settings.

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# Micro-morphological characterization of dry-farming soils at Yangshao site in China

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**ABSTRACT**

The dryland farming practices embodied in the Yangshao culture (5000–7000 B.P.) represent a precious agro-cultural heritage that profoundly influenced the development of Chinese civilization. Current research on primitive agricultural systems in northern China remains relatively limited. Enhancing the documentation and study of relevant farming techniques and heritage sites is therefore essential. Such work can provide a foundational basis for nominating significant sites as National or Globally Important Agricultural Heritage Systems.

This study employs an integrated methodology, including field survey of soil profiles, basic physico-chemical analysis, and soil micromorphology, to extract evidence of ancient cultivation from multiple cultural layers at the Yangshao Village site. The aim is to characterize agricultural practices during this critical period.

Results indicate that the cultural layers are predominantly gray-brown in color and contain inclusions such as pottery shards, bone fragments, and charcoal. These layers exhibit elevated total nitrogen content and significantly higher concentrations of total phosphorus and calcium carbonate compared to adjacent, non-anthropogenic soils. The soil matrix and aggregates within the cultural layers show marked heterogeneity, indicating the incorporation of diverse anthropogenic materials.

Micromorphological observations reveal specific features linked to human activity: iron oxides and black charcoal derived from fire use; crystals and aggregates associated with altered soil conditions; and fecal pellets likely resulting from organic matter addition (e.g., manuring). These features, along with micro-laminations and disrupted soil fabrics, provide direct evidence of soil cultivation, fertilization, and irrigation practices.

A strong correlation was found between the macroscopic observations, physico-chemical data, and micromorphological features. This multi-proxy correlation enabled the classification of activity areas at the site into zones of high and low probability for ancient cultivation. Paleotopographic reconstruction further suggests that early human activity, particularly cultivation, began in lower-lying areas. These practices appear to have contributed to the development of a stable, sponge-like soil microstructure.

In conclusion, the macroscopic and physico-chemical properties of the soils are fully consistent with the micromorphological evidence, confirming that these are anthropic soils (Anthrosols) formed through ancient human fire use and intensive farming. This research demonstrates the effectiveness of a multi-disciplinary approach in identifying and interpreting ancient agricultural practices, providing concrete evidence for the sophisticated land management of the Yangshao culture.

**Acknowledgments**

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# Species-Specific Impact of Earthworm Ecological Groups on Soil Coprolite Physico-Chemical Properties and Microstructure

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**ABSTRACT**

Earthworms function as critical soil ecosystem engineers, fundamentally altering soil physical architecture, porosity, and the effective circulation of nutrients, notably nitrogen (N) and phosphorus (P). Their activities enhance soil structure and fertility. This study investigated the distinct, species-specific impacts of three major ecological earthworm groups—Aporrectodea caliginosa (endogeic), Lumbricus terrestris (anecic), and Dendrobaena veneta (epigeic)—on the physico-chemical properties and microstructure of soil coprolites produced over a nine-week mesocosm period. The initial soil substrate had an alkaline pH of 7.83. Analysis included quantifying pH, Organic Carbon (OC), Total Nitrogen (TN), and the Carbon to Nitrogen (C:N) ratio. Advanced image segmentation of micromorphological thin sections was used to quantify the relative contribution of mineral matter, organic matter, and pore space fractions.

Coprolites generally exhibited a higher pH than the surrounding soil, confirming a known effect of earthworm activity. The endogeic species, A. caliginosa, produced coprolites with the highest OC (2.36%) and TN (0.22%) content. Furthermore, A. caliginosa created the most water-resistant aggregates, with a Water Resistance Index (WRI) of 0.59, confirming its role in strengthening soil structure. Conversely, the epigeic species, D. veneta, which relies primarily on surface organic matter, generated coprolites characterized by the lowest C:N ratio (7.75).

Micromorphological analysis revealed significant compositional differences linked to feeding strategy. D. veneta coprolites contained minimal mineral content (2.9%) and high organic fractions (65.9%). This contrasts sharply with the endogeic and anecic species (A. caliginosa and L. terrestris), which demonstrated strong mixing of the mineral soil component with organic matter. These results emphasize that the ecological grouping and associated feeding habits of earthworms drive distinct coprolite compositions, significantly influencing soil aggregation potential and nutrient availability.

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# Microscopic morphological characteristics of the Albic horizon in the Black Soil Region of Northeast China

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**ABSTRACT**

Albic soil, a typical low-yielding problematic soil in Northeast China's black soil region, faces the albic horizon as the primary impediment to agricultural productivity. This horizon is characterized by compact texture, limited nutrient and water mobility, nutrient deficiency, and uneven spatial distribution, which collectively restrict root penetration and severely constrain regional grain production and sustainable agricultural development. Through field surveys and microscopic analyses of thin sections from collected albic soil samples, this study systematically examines the morphological features of mineral composition, pore structure, and biotopes, alongside their interrelationships, to uncover the micro-mechanisms underlying albic horizon formation. The findings reveal that the albic horizon exhibits high silty sand and low clay content, with iron- and manganese-deficient pale leaching layers displaying 2–3 mm flake-like structures and an average thickness of 18–22 cm. Its pore structure demonstrates vertical reduction and horizontal expansion: under waterlogged conditions, ferric iron in the subsoil reduces to ferrous iron, with some migrating laterally via soil solution and others leaching downward through organic matter complexation; in arid conditions, ferrous ions oxidize back to ferric states, forming localized nodules that co-precipitate with clay. Furthermore, under acidic conditions—particularly from organic matter decomposition—aluminosilicates precipitate. During micro-scale precipitation, particles smaller than 0.25 mm form micro-aggregates or monoliths that coalesce into dense structures through cementation, potentially serving as the key micro-mechanism driving soil compaction. These insights collectively advance the understanding of albic horizon genesis and provide a scientific basis for mitigating its constraints on agricultural productivity in the region.

**Acknowledgments**

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# Magnetic properties and geochemical elements, climate change in loess/paleosol from the eastern Chinese Loess Plateau

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**ABSTRACT**

Loess-paleosol in the Chinese Loess Plateau is a valuable archive of climate change and soil pedogenesis. Nevertheless, knowledge of the interactions between soil magnetism and underlying geochemistry (i.e. geochemically relevant elements) are limited, especially on the eastern of Chinese Loess Plateau. To address this gap, we collected a new soil/paleosol sequence (21 m depth) and applied a range of rock magnetism methods, diffuse reflectance spectroscopy, and x-ray fluorescence measurements to establish a relationship between magnetic properties and geochemical element ratios from Fushan in the eastern of Chinese Loess Plateau. The results suggested that Fushan loess/paleosol sequence was deposited between 0.75 to 0.15 Ma, and is characterized by fine-grained magnetite/maghemite and goethite, with the single-domian (SD), pseudo-single domain (PSD) and multiple domain (MD) grain sizes. The correlation between magnetic susceptibility and Rb/Sr, Ca/Ti ratio in particular reflected the intense pedogenesis controlled by the East Asian summer monsoon. Magnetic susceptibility and diffuse reflectance spectroscopy revealed three significant climate change events corresponding to 1) specific stages of the global ice age (0.75 to 0.54 Ma), 2) a transitional period between the ice age and the interglacial period (0.54 to 0.28 Ma) and 3) the gradual approach of a new ice age (0.28 to 0.15 Ma). The relationship between soil magnetism and geochemical elements can therefore provide a new perspective for understanding past changes to climate.

**Keywords:** Soil magnetic properties, Geochemical elements, Climate change, Linfen basin, Loess-paleosol

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# Mineral magnetic characterization of surface soil in an industrial area within Guangzhou city: Implications for heavy metal pollution monitoring

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## ABSTRACT

Soil heavy metal pollution has becoming one of the most serious global environmental problems due to its potential impact on human health especially for urban industrial areas. As a method with advantages of rapidness, sensitiveness, cost-effectiveness, and non-destructiveness, environmental magnetism has been widely applied in many fields including soil heavy metal pollution monitoring. Many previous studies showed obvious soil magnetic enhancement along with increasing heavy metal contents and proved some magnetic parameters can be used for heavy metal pollution monitoring. However, the wide application of magnetic method in heavy metal monitoring is limited due to the complexity and spatial heterogeneity of the occurrence relationship between heavy metals and magnetic particles as well as the influences of natural pedogenic particles.

In order to unravel soil magnetic properties and their correlation and implication between/for heavy metal pollution for industrial areas within megacities, one hundred and two surface soil samples collected from the Huangpu industrial area within Guangzhou city were selected for detail environmental magnetic measurements. Based on statistical analyses of environmental magnetic results, thirteen and fifty-six representative samples were selected for rock magnetic and heavy metal content measurements, respectively. In order to unravel the relationship between heavy metals and magnetic minerals within topsoils, correlation and factor analyses are performed using environmental parameters (logarithmically transformed to conform to normal distribution) and *Igeo* of every heavy metal element as well as $I_{MN}$. Furthermore, multiple linear regression analysis (stepwise) was conducted using content of each heavy metal element (logarithmically transformed to conform to normal distribution) as the dependent variable and magnetic parameters as the independent variables.

The environmental magnetic results indicate that the main magnetic carriers within the measured soil samples are minerals of iron oxides within coercivity range from 20 mT to 300 mT. The values of concentration magnetic parameters are obviously higher and relatively high spatial variability than natural and agricultural soils within the study area (Bian et al, 2014; Chen et al, 2025). Within all measured samples, only one soil sample has similar $_{fd}$(%) value (6.1%) to natural formation soils, the $_{fd}$(%) values of other one hundred and one soil samples are less than 1%, suggesting that the contribution of SP to magnetic susceptibility can be neglected. Moreover, the $_{ARM}$/SIRM values of all measured soil samples are ranged from 2.65 to 62.21*$10^{-5}$ m/A, indicating that magnetic particles within soil samples are MD+PSD and Coarse SSD (Dearing et al, 1997). In addition, the King plot of all measured samples indicate that particle size of magnetic minerals are coarser than 0.2 m and even than 5.0 m. Rock magnetic results such as hysteresis loops, IRM acquisition and reverse demagnetization curves indicate that the remanent coercivity of all measured soil samples are less than 60 mT. Furthermore, magnetic susceptibility variation during heating processes illustrated by -T curves suggests the main magnetic minerals should be magnetite phase and some small amount of high coervicity minerals such as iron hydroxides or hematite. Consequently, three magnetic components with respective average $B_{1/2}$ of 4.7 mT, 43.3 mT, and 632.1 mT and respective average IRM contribution of 3.1%, 85.5%, and 11.4%, indicating the predominated coarse magnetite mineral phase.

According to soil heavy metal pollution assessment results published by Zhou et al (2022), most of the measured soil samples are moderately to seriously contaminated by heavy metals Cu, Zn, Pb, Cd. As shown in Figure 1, significant differences of magnetic properties are appeared among different pollution level soil samples.

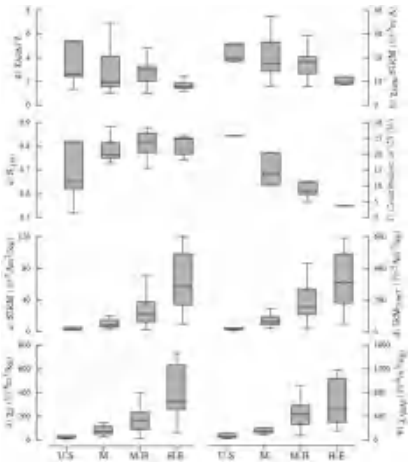


Figure 1 Comparison of magnetic properties among different pollution level samples (U-S, M, M-H, and H-E represent uncontaminated to slightly contaminated, moderately contaminated, moderately to heavily contaminated, and heavily to extremely contaminated, respectively). a) lf (10-8 m3/kg), b) ARM (10-8 m3/kg), c) SIRM (10-3 Am2/kg), d) IRM20mT (10-5 Am2/kg), e) S-100, f) IRM contribution of C3 (%), g) ARM/ , h) ARM/ SIRM (10-5 m/A)

Soil magnetism is significantly enhanced by anthrogenic input heavy metals due to continuous increasing values of concentration dependent magnetic parameters (Figure 1a, b, c, d) along with more seriously pollution. The values of $S_{-100}$ (Figure 1e) and IRM contribution of C3 (Figure 1f) are respectively increased and decreased from uncontaminated to extremely contaminated samples, indicating a decreasing content of natural pedogenic hematite with increasing heavy metal pollution. The variation trends of ratio parameters (Figure 1g, 1h) further proved that magnetic particles are become coarser along with the increasing heavy metal pollution.

Except for Hg, *Igeo* of other heavy metals and $I_{MN}$ are significant positively correlated with concentration dependent magnetic parameters $_{lf}$, $_{ARM}$, $_{fd}$, SIRM, HIRM, $IRM_{20mT}$ as well as S-ratio. On the contrary, significant negative correlations are appeared between HARD, $_{ARM}$/SIRM and *Igeo*, $I_{MN}$. The mentioned results manifest that heavy metals are coexisted with coarser low coercivity magnetic particles. *Igeo*_Hg is positively correlated with $_{ARM}$, $_{fd}$, SOFT, $_{ARM}$/SIRM, and $_{ARM}$/ , indicating that Hg should be coexisted with low coercivity fine magnetic particles such as SP and SD magnetite.

Factor analysis yields four principal components with Eigenvalue larger than 1, explaining 84.9% of the cumulative variance. The C is significantly positive correlated with magnetic parameters $_{lf}$, $_{ARM}$, $_{fd}$, SIRM, HIRM, $IRM_{20mT}$, $S_{-300}$ and $I_{geo}$ of heavy metals Cu, Zn, Ni, Pb, Cr, Cd, As, and comprehensive pollution index $I_{MN}$, indicating that C1 can represent the anthrogenic input of the mentioned heavy metals and most of magnetic particles. As for the second principal component, ratio magnetic parameters SIRM/ , $_{ARM}$/ $_{ARM}$/SIRM and $I_{geo}$_Hg have significant positive loadings, suggesting C2 may represent input of finer magnetic particles. Simultaneously, $I_{geo}$_Hg is also significantly positive with C4 which has obvious high loading for $S_{-300}$. These results indicate that Hg may be coexisted with fine low coercivity magnetic particles. Except for a positive correlation with C1, HIRM is concurrently negative related with C3. Meanwhile, C3 is also positively related with $S_{-300}$. Therefore, it can be deduced that C3 should represent generation of hematite through natural soil formation. Interestingly, no obvious correlation is appeared between C3 and all measured heavy metals, proving that these heavy metals are derived from anthrogenic sources.

According to the less than 0.001significance reflected by the $R^2$ values and scatterplots between predicted and measured cumulative probability (P-P plots), it can be concluded that the regression models are reliably and can be used to analyze the occurrence of heavy metals and magnetic particles and to predict soil heavy metal contents. Contents of Cu, Zn, and Cr can be predicted and inverted using SIRM which reflects the content of magnetic particles (especially coarser particles), indicating that these elements may be tended to coexist with coarser magnetic particles in soils. Heavy meatal Ni can be predicted and inverted by $_{ARM}$ and SOFT (respectively positive and negative correlation), indicating that Ni in soil tends to coexist with SD magnetic particles with a coercivity greater than 20mT. Heavy metal As can be predicted and inverted using $_{ARM}$, indicating that As in soil tends to coexist with SD magnetic particles. Pb in soil tends to coexist with magnetic particles coarser than SP particles. Cd can be positively predicted and inverted using SIRM and $S_{-300}$, indicating that Cd in soil tends to coexist with coarser soft magnetic particles. In the regression model for Hg, magnetic parameters $_{ARM}$/ and $S_{-300}$ are selected and positively correlated, indicating that Hg in soil tends to coexist with finer soft magnetic particles. Overall, soil heavy metal pollution is mainly affected by anthrogenic input of coarse magnetic particles with coercivity greater than 20mT. Therefore, magnetic parameters SIRM, $IRM_{20mT}$, and $S_{-300}$ are suggested for soil heavy metal pollution monitoring within industrial areas.

The present findings and the established regression models can give some References for deep understanding of magnetic response to soil heavy metal pollution and the application of magnetic method in soil heavy metal monitoring.

# Study on Optically Stimulated Luminescence Dating and developmental model of alpine meadow soil in ThreeRiver Headwater Region

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**ABSTRACT**

The formation age and pedogenic development of alpine meadow soils in the Sanjiangyuan (Three Rivers Headwater) region are crucial for understanding soil-forming processes on the Qinghai–Tibet Plateau. In this study, twenty-one alpine meadow soil profiles were investigated across the Sanjiangyuan area. Optically stimulated luminescence (OSL) dating was applied to both the grass-mat (turf) layer and the parent-material layer, and particle-size characteristics were analyzed to reconstruct soil developmental processes. In addition, soil magnetic properties were considered as complementary indicators of pedogenic intensity and dust input.The results show that the grass-mat layer of alpine meadow soils generally formed within the last 1 ka, whereas most parent-material layers developed since the last deglaciation, with a few dating to interstadial phases of the Last Glacial period. Grain-size distributions of parent materials commonly display a distinct trimodal pattern, with a dominant peak at 40–60 μm. The grain-size frequency curves closely resemble those of typical loess deposits, indicating that aeolian dust represents a major source of soil parent material in the region. Consistent with the grain-size evidence, enhanced pedogenic magnetic signals in surface and near-surface layers suggest intensified pedogenic modification and effective trapping of fine aeolian particles during soil development.From the last deglaciation to the Holocene, climatic fluctuations exerted strong control on dust-input rates and pedogenic intensity. Parent-material ages cluster mainly in the late Holocene, implying strengthened aeolian activity under cold–dry climatic conditions, which provided essential materials for alpine meadow soil formation. Overall, the combined evidence from OSL chronology, particle-size characteristics, and soil magnetic properties demonstrates that alpine meadow soils in the Sanjiangyuan region developed under a “mixed parent material–aeolian accretion” pedogenic model, highlighting their high sensitivity to climatic and environmental changes.

**Keywords:** Three Rivers Headwater Region; alpine meadow soil; OSL dating; grain-size distribution; soil development

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# Impacts of Vehicular Non-Exhaust Emissions on Magnetic Enhancement and Heavy Metal Accumulation in Urban Road Dust

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**ABSTRACT**

In recent years, with the popularization of electric vehicles and improvement of fuel quality, vehicular exhaust emissions have significantly decreased, while the proportion of non-exhaust emissions has increased. Non-exhaust emission particles are characterized by their fine size and complex composition, of which, the friction particles from vehicular brakes contain 43%-75% of metallic Fe and Fe oxides, and 1-2% of other metals. Fe-rich particles tend to adsorb heavy metals such as Ni, Cu, Zn, Ba, Cd, Pb, and Mn within their structure tightly. Therefore, magnetic parameters can be used to evaluate the content of Fe and heavy metals in soil and sediments.

Fe-containing fine particles from industrial activities and vehicular non-exhaust emissions have become a major source of suspended magnetic particles in urban atmosphere. To study the impact of deposition of atmospheric magnetic dust on the urban environment and soils, a total of 203 dust samples were collected on solidified road surface in the areas strongly influenced by traffic, commercial or industrial activities in Shanghai, Southeast China. Each dust sample was divided into coarse (0.149-2 mm) and fine (<0.149 mm) fractions. Their magnetic, geochemical, and mineralogical properties of the dust were analyzed, compared with these of powder of brake pads. Magnetic susceptibility (χlf) of the coarse and fine fractions of the road dust was 555.69 × 10-8 m3 kg-1 and 667.88 × 10-8 m3 kg-1 on average, respectively, which was 19-23 times the magnetic background value of the soils in Shanghai. The χlf of the road dust in the different areas followed the decreasing order of the industrial area > the traffic > the residential. Frequency-dependent susceptibility (χfd%) of the road dust was mostly less than 2%, indicating that the magnetic particles in the road dust were dominated by anthropogenic coarse multi-domain (MD) and stable single-domain (SSD) particles. The χlf value of the road dust was significantly negatively correlated with the content of Cd, Co, Cr, Fe, Mn, Ni, Zn, and the pollution load index (PLI) ($p<0.01$), suggesting its effectiveness as a pollution indicator. The source analysis indicated that the industrial activities dominantly contributed Fe, Mn, Ni and Cr in the road dust, while the brake wear is an important source of Ba, Cu, Sb, Pb and Zn. The Cu/Sb ratio in the coarse fraction of the road dust in the traffic, industrial and residential areas was 11.40, 20.75 and 22.66 on average, respectively. That in the traffic area was close to the characteristic value of brake wear particles (4.6 ± 2.3). The fine fraction of the road dust in the different functional areas showed the similar patterns of Cu/Sb ratio. This highly suggests the significant influences of vehicle non-exhaust friction wear particle emissions, especially brake wear particle release, on road dust accumulation. Continued atmospheric magnetic dust deposition profoundly affects urban surfaces and soil formation.

# Vertical distribution of magnetic property of urban soil profiles in Shanghai and its environmental implications

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## ABSTRACT

Eighteen soil profiles were set up in the five areas, including an agricultural field at Luojing Town, a residential area at Dachang Town, a greening belt beside traffic lines, and industrial sites at the Shidongkou and Wusong Parks in Baoshan District in the northern part of Shanghai, Southeast China, to study the magnetic characteristics and heavy metal contents in the urban soils.

The agricultural soil has a weaker magnetic signature, close to the local magnetic background. In contrast, the magnetic signatures of the soils in residential, traffic lines, and industrial areas are significantly enhanced. The magnetic susceptibility (χlf) of the soil profiles in the agricultural field, residential area, traffic green belt, and Shidongkou and Wujiang industrial Parks, are 26.5×10-8 m3 kg-1, 60.5×10-8 m3 kg-1, 80.4×10-8 m3 kg-1, 108×10-8m3 kg-1, and 269×10-8 m3 kg-1 on average, respectively. Correspondingly, the content of heavy metals in the agricultural soil is relatively lower with the average of Cr, Cu, Pb, Zn, Cd, Ni, Co, Mn, and Fe being 73.3 mg kg-1, 19.2 mg kg-1, 16.6 mg kg-1, 50.4 mg kg-1, 0.599 mg kg-1, 34.9 mg kg-1, 19.8 mg kg-1, 0.792 g kg-1, and 33.0 g kg-1, respectively; that in the traffic and residential soils is increased; that in the industrial soils is the highest. For example, the content of Cr, Cu, Pb, Zn, Cd, and Mn in the soil of the Wusong industrial Park is 455 mg kg-1, 30.3 mg kg-1, 73.2 mg kg-1, 149 mg kg-1, 1.44 mg kg-1, and 1.67 g kg-1 on average, which is 6.01, 1.29, 3.44, 1.97, 4.11, and 2.0 times the magnetic background of the Shanghai soils.

The magnetic characteristics and heavy metal contents of the soil profiles in the different areas show significant differences in vertical distribution. The χlf and heavy metal content in the surface of the agricultural soil profiles are slightly higher; but below 30 cm, it rapidly decreases and tends to be stable. There are large industrial parks or other pollution sources around the agricultural area. The studied agricultural field is located at the downwind direction of Shanghai Shidongkou Power Plant, and the increase of heavy metals in the surface layer may be related to the deposition of pollutants from industrial sources.

The χlf and heavy metal content fluctuate significantly in the middle and lower layers of the soil profiles in the greening belt of traffic lines and residential area. The fluctuations in the residential soils may be due to the historical disturbance, when the polluted soil in the area was turned over and buried in the lower layer; and these in the greening belt may be related to the planting of vegetation, which will turn the polluted soil exposed on the surface into the lower layer.

The χlf and heavy metal content of the industrial soil profiles in the Shidongkou Industrial Parks and the Wusong Industrial Parks are very high in the surface layers (0-5 cm), and greatly fluctuate in the middle and lower layers. The abnormal increase of χlf in the surface is related to the deposition of a large number of magnetic particles carried by suspended particles such as coal-fired fly ash and steelmaking dust from power plants in the region, while the large fluctuations in the middle and lower layers are also related to the invasion of artificial pollutants in the historical period.

The χlf value of the agricultural soils is significantly positively correlated with the content of Cr, Cu, Pb, Ni, and Fe ($p<0.05$); that in the traffic soils is significantly positively correlated with Cu, Pb, and Zn; that the industrial soils is extremely significantly positively correlated with a variety of heavy metals ($p<0.01$), with high correlation coefficients; however, there are no such correlations in the residential soils. Nevertheless, the χlf of all soil samples in this study is significantly positively correlated with the content of Cr, Cu, Pb, Z, Cd, Ni, Co, Mn, and Fe ($p<0.05$). This suggests that χlf in the urban/industrial soils in Shanghai has a good indicative significance for the accumulation of heavy metals.

# Magnetic Characteristics of Typical Soils in Guangdong Province and Their Responses to Parent Materials and Land Use

**Lu Ying Zhuang ZI-kun Lai Zhi-ming Cui Luo-xiao**

**ABSTRACT**

Soil magnetic properties serve as vital proxies for understanding pedogenic processes and environmental evolution. This study investigated 199 typical soil profiles in Guangdong Province, characterized by intense weathering and diverse parent materials. Key parameters, including low- and high-frequency magnetic susceptibility (Xlf、Xhf), frequency-dependent susceptibility (Xfd), and preliminary remanence data, were measured to analyze spatial distribution and controlling factors. The main findings are as follows: Parent material is the primary factor determining the background magnetic intensity. Significant differences in Xlf were observed among soils derived from different parent materials, with mean values decreasing in the order: Basalt (424.92×10-8m3/kg)≫ Sandstone (36.51×10-8m3/kg)≈ Granite (36.29×10-8m3/kg)> Sediments (28.65×10-8=m3/kg).The extremely high magnetic background of basalt-derived soils reflects the substantial contribution of primary ferrimagnetic minerals from basic rocks. Land-use patterns significantly modified the magnetic characteristics of topsoils. Results showed that the mean Xlf of forest topsoils （50.60×10-8m3/kg） was significantly higher than that of paddy soils （16.63×10-8m3/kg）. This indicates that natural pedogenesis leads to magnetic enhancement, whereas long-term flooding and reductive conditions (gleying) in paddy fields cause the reductive dissolution of magnetic minerals, resulting in a marked decrease in intensity. A positive correlation between Xfd% and Xlf suggests the widespread presence of pedogenic superparamagnetic (SP) and single-domain (SD) grains in Guangdong soils. Preliminary analysis indicates that ferrimagnetic minerals are the dominant carriers of soil magnetism in the study area. The spatial distribution of soil magnetic susceptibility in Guangdong exhibits strong lithogenic inheritance and is profoundly modified by anthropogenic hydro-pedogenesis. This study provides a scientific baseline for soil genesis and environmental assessment in South China.

**Key words:** Magnetic susceptibility; Parent material; Stagnic Anthrosols; Frequency-dependent susceptibility；Guangdong Province

# Redefining soil structural vulnerability to enhance ecosystem services in a changing world

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**ABSTRACT**

Soils sustain life by filtering water, cycling nutrients, supporting biodiversity, and enabling food production, and thus is a fundamental resource for advancing the UN Sustainable Development Goals. The ecosystem services provided by the soil are fundamentally dependent on its structure, which defines the very nature of soil, mediating the interactions among air, water, minerals, and biota that underpin all soil-derived ecosystem services. Yet intensive management practices, such as frequent tillage, heavy machinery, livestock treading, and deforestation threaten the critical soil structure. This potentially jeopardises food security, increases greenhouse gas emissions, accelerates erosion, and impairs water storage and quality. Such impacts are likely to amplify under climate change.

The degradation of soil structure and associated losses in soil functions and ecosystem services are related to soil structural vulnerability (SSV). Current SSV assessments are based on static properties that poorly predict the soil functions needed to forecast changes in ecosystem services, both positive and negative, including plant production and greenhouse gas emissions We propose that SSV, analogous to human disease vulnerability, should be defined by the soil's ability to sustain and recover its functions and services under external pressures.

Using literature review, data synthesis, our controlled experiments and modelling, we demonstrate how dynamic functional properties of contrasting soil types respond to compaction, and how these responses influence plant productivity and $N_2O$ emissions. We highlight the need to assess SSV through the responses of dynamic soil functions and their consequences for ecosystem services. We advocate for a functional and service-oriented soil management framework that incorporates SSV into adaptive, outcome-focused, decision-making tools. Such a system is essential for enhancing soil resilience and safeguarding ecosystem services under changing climates and land uses.

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# Viral Diversity in Different Types of Purplish Soils

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**ABSTRACT**

Purplish soils are a typical agricultural soil type in the upper Yangtze River region, and differences among soil types significantly affect soil quality and nutrient cycling processes. As key regulators of microbial metabolism and nutrient transformation, viruses play important ecological roles. However, their community characteristics and functional differentiation across different types of purplish soils remain poorly understood. This study focused on three typical purplish soils from Sichuan Province: acid (AC), neutral (NE), and alkaline (AL) types. Using high-throughput viromic sequencing, we systematically analyzed viral diversity, metabolic functional differences, and virus–host interaction patterns across different soil pH conditions. Viral diversity was highest in AL soils and lowest in NE soils. However, NE soils had the greatest abundance of viral genes associated with carbon, nitrogen, and phosphorus metabolism, and showed the most complete pathway coverage, including key metabolic enzymes such as porA, ack/acs, and ppx/ppa. The predicted host community in NE soils was taxonomically diverse, including Cyanobacteriota, Actinomycetota, and Pseudomonadota, with strong potential for carbon fixation and extracellular polysaccharide degradation. In AL soils, viral functions were enriched in key genes like phoB/R and amoA, suggesting roles in phosphorus acquisition/regulation and nitrification, with hosts such as Candidatus Dadabacteria and Verrucomicrobiota. In AC soils, viruses were enriched in gcd and pstC/A genes related to high-affinity inorganic phosphorus solubilization and uptake, suggesting that viruses may enhance phosphorus acquisition under acidic, nutrient-limited conditions.These results demonstrate that viruses and their hosts form distinct interaction networks in different purplish soil types, reflecting their regulatory potential in nutrient utilization strategies. This mechanistic understanding offers theoretical guidance for improving soil quality and optimizing fertilization practices based on microbe–virus interactions.

# Silicon cycling model and its roles on soil evolution in a subtropical critical zone

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**ABSTRACT**

Silicon (Si) is one of the most important elements of the Earth surface. Biogeochemical cycling of Si influences the processes of weathering, leaching, plant uptake and transformation. However, the roles and contributions of Si translocation and transformation on soil genesis and evolution in subtropical areas with ample weatherable silicates is largely unknown in the critical zone.

A typical forested watershed and two forest-agriculture watersheds located in southern Anhui Province, subtropical China were selected to study Si cycling and soil evolution. The main crop was rice and the main forests pecies were pine, fir, chestnut, bamboo, shrubs and grass. The main soil types are Lithic Udorthents, Lithic Dystrudepts and Typic Epiaquepts derived from granite. The rock and soil physical, chemical and mineralogical characteristics were measured. Si and base cations cycling amount among rock, soil, plant, water and atmosphere were determined.

High Si uptake by plant significantly increased the mineral weathering and soil formation rates. Therefore, the weathering and soil formation rates estimated from net output by stream without consideration of the effects of plant would be greatly underestimated. Desilification and resilification coexisted in the subtropical area during soil formation. Plant growth was very important to Si cycling, not only increased the primary mineral weathering, but also redistributed Si in the soil profile and enriched Si in the surface soil. Plant species greatly affect the amount of Si cycling and phytolith-Si concentrations in soil. High Si accumulators could assimilate and return more Si than low accumulators, and also enrich more biological Si in the surface soil.

Therefore, Biological Si cycling plays an important yet secondary role in the subtropical soil development. Silicate weathering dominates Si flux between soil-plant system. Agricultural activities and plant species affect Si translocation and redistribution in soils. Different plants represented soil desilication or resilication according to its ability in cycling Si.

**Keywords:** Si translocation; Soil genesis and evolution; Soil formation; Soil desilification; Silicate weathering

**Acknowledgments**

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# Prediction of Soil Structural, Hydraulic, and Chemical Properties: A Comparison of NIR and MIR Across the Critical Zone

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**ABSTRACT**

Soil structure built from aggregates and mineral–organic bonds controls water movement and biogeochemical processes in the Earth's Critical Zone. Scalable approaches for quantifying these properties are needed to assess ecosystem resilience under changing environmental conditions. This study compares near-infrared (NIR) and mid-infrared (MIR) spectroscopy for predicting key structural, hydraulic, and chemical soil properties using 1,976 samples from the Open Soil Spectral Library, collected primarily from the United States. NIR spectra were acquired using a Neospectra portable spectrometer, while MIR spectra were collected using Bruker Alpha II and Bruker Vertex 70 instruments equipped with an HTS-XT attachment. Baseline correction and standard normal variate preprocessing were applied to reduce baseline shifts and spectral variability. Models trained on NIR spectra showed strong performance ($R^2 \approx 0.80–0.95$) only for total sulfur and $CaCO_3$, and moderate accuracy ($R^2 \approx 0.50–0.80$) for organic carbon, total carbon, cation exchange capacity, potassium, magnesium, pH, and clay. NIR struggled with structure-controlled properties such as field capacity and permanent wilting point, where most models produced $R^2 < 0.50$. In contrast, MIR spectroscopy achieved consistently higher accuracy across nearly all soil properties. MIR produced $R^2 \approx 0.80–0.98$ for organic carbon, total carbon, total sulfur, $CaCO_3$, cation exchange capacity, pH, clay, sand, and permanent wilting point, with moderate performance ($R^2 \approx 0.50–0.80$) for total nitrogen, electrical conductivity, bulk density, and field capacity. These gains reflect MIR's ability to resolve absorptions linked to clay minerals, carbon functional groups, and microaggregate features—key drivers of water retention and pore continuity. Across both NIR and MIR regions, Categorical Boosting, Random Forest, Cubist, Artificial Neural Networks, Least Absolute Shrinkage and Selection Operator, Elastic Net Regression, Ridge Regression, and Partial Least Squares Regression performed well, with the strongest results in the MIR region. These models captured mineralogical, structural, and biogeochemical signals more effectively, improving predictions of soil structural, hydraulic, and chemical properties. Overall, MIR provides a more robust platform for quantifying soil structural, hydrological, and biogeochemical functioning, while NIR offers a rapid and portable alternative where moderate accuracy is acceptable. Future work should examine whether spectroscopy can reliably predict biological soil indicators—such as microbial biomass, enzymatic activity, and labile carbon fractions—to integrate physical, chemical, and biological dimensions of Critical Zone soil health.

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# Implications of land uses and land cover conversion on soil quality in the Lower Alwero watershed Gambela Region Western Ethiopia

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**ABSTRACT**

Land use and land cover (LULC) changes, driven by policy interventions and shifting socioeconomic activities, have raised increasing environmental concerns and contributed to land degradation in Ethiopia's lowlands. Over the past three to four decades, these changes have altered landscape structures, including the Lower Alwearo watershed, often resulted unintended ecological consequences, such as declining soil quality. Therefore, the objective of this study was to assess the effect of LULC changes on soil health using a set of scientifically validated soil quality indicators. A total of 131 disturbed and 58 undisturbed soil samples were collected across different LULC types and analyzed for key physicochemical properties. The samples were analyzed for standard attributes in the laboratory, and the results were subjected to Principal Component Analysis (PCA) to identify a Minimum Data Set (MDS) of the most influential soil indicators, which informed the construction of a Soil Quality Index (SQI) using a weighted additive approach. Statistical analysis showed a significant difference in soil quality indicators across LULC types. Among the LULC types, there is a clear trend in the variation of SQI values decreasing from natural forests and grasslands (1.0) to mechanized farmlands (0.86), largely due to intensive tillage and nutrient depletion, whereas smallholder farmlands benefit from minimal disturbance and traditional conservation practices. Woody grasslands showed moderate soil quality (SQI = 0.90), reflecting the effects of biomass extraction and grazing pressure. Seven key soil quality indicators, such as total nitrogen, cation exchange capacity, exchangeable calcium, exchangeable magnesium, available phosphorus, and bulk density were identified as critical metrics for soil quality monitoring in the watershed. Despite widespread land conversion, overall soil quality remains relatively high, partly due to under-utilization of cleared land and continued reliance on indigenous land management practices. The study recommends integrating these indicators into land use monitoring frameworks to guide sustainable land management. It further emphasizes the importance of conservation-based agriculture, regular soil assessment, and the incorporation of indigenous conservation practices into policy design to ensure environmental resilience and agricultural productivity in Ethiopia's lowland ecosystems and beyond.

**Key words:** soil quality indicator, land use and land cover change, soil attributes, GIS, remote sensing, degradation, environment

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# Analysis for structure of soil layer composed of large clods using X-ray CT image

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**ABSTRACT**

Large clods with some centimeters are formed by tillage in a clayey paddy field. As the clod size becomes larger, the water vapor movement is strongly enhanced due to wind, while the unsaturated hydraulic conductivity remains almost unchanged. These characteristic water vapor and liquid water movement in the soil layer composed of clods (SLC) results from the arrangement of clods and inter-clod pore spaces. However, the effect of clod size on these soil structure still remains unclear. In this study, we analyzed the soil structure of SLC with different diameters using X-ray CT images.

We sampled four kinds of SLC from the surface of paddy fields in triplicate using the PVC column with a diameter of 15.4 cm and a height of 9.7 cm just after tillage. The mean clod diameters (MCDs) of these SLCs were 0.8, 2.0, 2.4, 4.1 cm. The SLCs were scanned by the industrial X-ray CT scanner with a tube voltage of 150 kV. The obtained projections were reconstructed to 3D volume and then converted to the 16-bit image stacks with a image resolution of 94.4 or 95.0 µm. The image analysis was conducted using SoilJ (Koestel, 2017), which is the plugin of Fiji. The median filter and unsharp mask filter were applied to the image stacks. The region of interest was designated as the inside of column wall, bottom of the column, and 26 mm below the top of the column. The artifact of beam-hardening was corrected and the gray values of each image slice were standardized. And then, Otsu segmentation method was applied to separate the clods and inter-clod pore spaces. Using the function of "PoreSpaceAnalyzer" in SoilJ, following properties were obtained: porosity and averaged diameter for inter-clod pore spaces; profile of clod fraction and critical diameter for clods; connectivity and percolating fraction for both.

As a result, for the inter-clod pore spaces, the connectivity and percolating fraction was almost unity in all SLC. As the MCD increased, while the porosity (0.31-0.43) slightly decreased, the averaged dimeter markedly increased from 1.1 to 8.0 mm. These results indicated that the enhancement of water vapor movement by wind can be influenced by the size of inter-clod pores. On the other hand, for the clods, the connectivity and percolating fraction was also almost unity in all SLC. As the MCD increased, while the critical diameter markedly increased from 1.0 to 13.1 mm, the clod fraction was close across SLCs. These results indicated that the unsaturated liquid water movement can be prescribed by the clod fraction of cross-sectional area in SLC.

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# Microstructural controls on carbon cycling and nematode communities across land-use agroecosystems and climate scenarios

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**ABSTRACT**

Soil structure fundamentally regulates biotic processes and ecosystem functioning in the Earth's Critical Zone. Organic inputs, together with the configuration of pores and biopores, control hydrological and aeration processes and govern the spatial availability of organic substrates, thereby shaping microbial activity, soil fauna niches, and root growth. However, the extent to which microstructural development shapes carbon cycling and soil food-web dynamics across contrasting land-use systems and under the future climatic scenario remains insufficiently understood. Using the Global Change Experimental Facility, which includes two annual croplands and three perennial grasslands under ambient and future climate scenarios, we integrated deep-learning-based X-ray CT segmentation, biogeochemical measurements, and soil nematode assessments to quantify microstructure–function linkages in soils.

Grasslands exhibited persistently higher volume fraction of particulate organic matter (POM), biopore, and root-derived structures due to continuous root inputs and the absence of tillage, leading to the formation of stable microstructure characteristic within 4–5 years. Croplands, in contrast, showed greater proportions of fresh roots, but reduced decaying roots and biopores, reflecting seasonal growth pulses and structural disturbance by plowing. Microbial biomass carbon and extractable organic carbon were consistently higher in grasslands, whereas total soil organic carbon displayed a slower degree of divergence among land-use systems. Climate treatments mainly influenced heterotrophic respiration through soil moisture, while exerting negligible effects on microstructure or carbon fractions. Across systems, POM volume, rather than pore structure, was the dominant predictor of carbon mineralization, probably because aeration of microbial hotspots was not limiting.

By explicitly linking microstructure to soil biota, we found that nematode communities responded strongly to land use and seasonality but only weakly to climate manipulation. In cropland soils, nematode abundance and composition were tightly coupled to microhabitat properties such as nematode-specific porosity, pore connectivity, and POM volume, indicating a strong bottom-up regulation by resource accessibility. In grasslands, however, nematode communities were largely decoupled from measurable structural and biochemical properties and instead exhibited stronger and more complex co-occurrence networks among nematode taxa, which may reflect higher functional redundancy, shared environmental pReferences, or stronger biotic interactions. Climate effects on nematodes were subtle, varied with season and land use, and were not mediated by microhabitat changes.

Together, these findings demonstrate that soil microstructure serves as a central organizing constraint on carbon cycling and nematode community structure, but its regulatory strength depends strongly on land-use-driven resource inputs.

# Straw incorporation mitigates polyethylene residual film-induced suppression of fungal necromass

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**ABSTRACT**

In arid and semi-arid farmlands, polyethylene residual film (PRF) poses a serious threat to soil ecological functioning. In agricultural practices, PRF frequently coexists with straw. However, the mechanism underlying their synergistic effects on soil organic carbon (SOC) turnover remains unclear. To investigate this, 13C stable isotope tracing, 16S/ITS absolute quantitative sequencing, and amino sugar biomarker analysis were employed to elucidate the mechanisms of SOC turnover under PRF addition alone [0.06% (R1) and 0.12% (R2), w/w] and in coexistence with straw [1.2% (S), w/w]. PRF alone (R1/R2) significantly suppressed fungal abundance, reducing fungal ITS rRNA gene copy numbers by 21.46% and 21.94%, respectively, which in turn decreased fungal necromass carbon by 12.86% and 3.32%. In contrast, the coexistence of PRF and straw (SR1/SR2) generated heterogeneous microsites through the combined effects of PRF hydrophobicity and straw porosity. This enhanced the priming effect and promoted straw decomposition. Meanwhile, these changes were accompanied by 8.94% and 3.41% increases in fungal abundance and fungal necromass carbon, respectively, ultimately stabilizing SOC. Notably, under SR2, physical degradation and weak carbonyl peaks indicated early-stage plastic degradation. Overall, straw alleviates PRF-induced fungal suppression, transforms PRF from pollutant to structural modifier, and reshapes microbial necromass carbon pathways, promoting SOC retention.

**Keywords:** Arid and semiarid agriculture; Straw incorporation; Polyethylene residual film pollution; Priming effect; Amino sugars

# Geodiversity-Driven Patterns of Prunus ledebouriana in Tarbagatay Mountain Landscapes of SE Kazakhstan

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## ABSTRACT

In arid mountain ecosystems, geodiversity, including microtopography, slope orientation, and geomorphological complexity, plays a fundamental role in regulating the redistribution of water and nutrients. These terrain-driven processes shape vegetation patterns and contribute to the formation of “fertile islands”: discrete shrub patches that enhance local soil properties and ecosystem functioning. In the southern Tarbagatai Mountains of southeastern Kazakhstan, the endemic wild almond (Prunus ledebouriana) forms persistent shrub communities between 600 and 1200 m a.s.l., contributing to landscape-scale vegetation mosaics and modifying soil conditions.

This study investigates whether topographic variables (as proxies for geodiversity) or soil properties better explain (i) the spatial dominance of almond shrub patches and (ii) their functional performance. We surveyed 56 plots distributed along elevation and terrain-position gradients within a typical valley on the southern slope of the Tarbagatai range, where P. ledebouriana naturally occurs. To explore the relationships between environmental variables and shrub performance, we applied regression-based analyses supported by model selection criteria.

Our results show that among all tested variables, topographic position, particularly “distance from the top” was the strongest predictor of shrub cover ($p < 0.001$). In contrast, average shrub height was more strongly associated with soil properties, especially electrical conductivity ($p = 0.047$), suggesting that salinity influences structural development. Lithological variation, including differences among colluvium, slope deposits, loess, and eluvium, also affected shrub height, with eluvial substrates associated with reduced stature ($p= 0.027$).

Functional leaf traits followed similar patterns. Chlorophyll content was primarily influenced by soil porosity ($p = 0.035$), with copper concentration further improving model performance and potentially acting as a limiting micronutrient in some sites. In contrast, the leaf N:P ratio was significantly related to topographic position, with higher values observed downslope ($p < 0.001$), indicating slope-driven variation in nutrient limitation regimes.

To synthesise these findings, we developed a Shrub Health Index (SHI) integrating morphological and physiological traits. The stronger association of the SHI with soil characteristics than with topographic variables supports a dual control framework, in which geodiversity governs the spatial establishment of almond shrubs, while soil properties regulate their functional performance. These insights advance our understanding of how intersecting terrain and soil factors shape perennial vegetation structure in arid mountain systems, with direct implications for predicting ecosystem responses to increasing aridity.

**Acknowledgments**

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# Seasonal Soil Hydraulic Function and Pore Size Dynamics throughout Cover Crop–Corn Rotation in a Reduced-Tillage System

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## ABSTRACT

Knowledge of soil structure and hydraulic properties is essential for hydrological modeling and agricultural water management. These properties are well known to exhibit substantial temporal variability in response to climatic conditions, biological activity, and anthropogenic interventions. For instance, tillage can temporarily increase macroporosity, near-saturated hydraulic conductivity, and water infiltration, although these effects typically diminish over time. Meanwhile, management practices such as incorporating cover crops into rotations and applying manure have been shown to enhance soil structural stability, improve water infiltration, and increase soil water-holding capacity. However, quantitative assessments on the short-term dynamics of soil hydraulic properties under reduced tillage systems remain limited. To address this knowledge gap, this study aimed to frequently quantify soil hydraulic properties and pore size distribution throughout the winter cover crop and subsequent corn seasons under reduced tillage with cover crop and manure treatments in the humid Southeast United States. Hydraulic conductivity at multiple tensions, soil water retention curves (SWRC), bulk density (BD), and pore size distributions (PoSD) were measured on undisturbed soil samples collected at five key sampling dates, including post-tillage, mid-cover crop season, pre-cover crop termination, mid-corn season, and pre-corn harvest. The results provide valuable insights for improving agricultural water management in humid regions and highlight the importance of accounting for temporal variability of soil hydraulic properties in hydrological models.

# Multifractal scaling of soil particle size distribution validates aggregate stability and pedogenic processes along a semi-arid erosional gradient.

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## ABSTRACT

Understanding soil structure is essential for evaluating land degradation, especially in vulnerable semi-arid regions. This study assessed the efficacy of fractal and multifractal parameters of the particle-size distribution (PSD) as process-sensitive indicators of soil structural stability and pedogenesis. Here, 14 soil horizons from three profiles (P1, P2, P3) situated along a semi-arid erosional gradient were examined, assessing essential soil properties including soil organic carbon, electrical conductivity (EC), mean weight diameter (MWD) and water-stable soil aggregates (WSA) and computing an extensive array of fractal descriptors (Df, D1, D2, Δα). The findings revealed robust, physically significant correlations between the fractal parameters and soil functional properties. The single-fractal fragmentation dimension (Df) had a strong link to aggregate stability. This showed that finer soil textures (higher Df) were linked to more stable aggregates (higher MWD, r=0.67; lower WSA, r=-0.62). This substantiates Df as a reliable metric for the principal textural determinants of soil stability, wherein fine particles serve as essential binding agents. The multifractal analysis also gave a lot of new information about how pedogenic pathways work. The generalised dimension spectra (D(q) vs. q) acted as unique "fingerprints" for each of the soil profile, clearly separating classic illuviation (P1, with a simple eluviated layer over a highly complex argillic subsoil), geological stratification (P3, defined by an unusual, coarse-textured sandy layer), and complex accumulation processes (P2). There was a positive correlation (r=0.55) between multifractal heterogeneity (Δα) and electrical conductivity (EC). This quantitatively linked the complexity of soil structure to landscape-scale accumulation processes along the semi-arid erosional gradient. In conclusion, this integrated fractal/multifractal methodology offers a robust, quantitative framework. It effectively correlates PSD geometry with soil function and identifies distinct pedogenic histories, demonstrating that these parameters are highly sensitive indicators of soil stability and development in intricate semi-arid landscapes.

**Keywords:** Arenosols; Botswana; Kalahari sand; Pedogenesis; Soil erosion

**Acknowledgments**

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# Co-applying straw biochar with green manure promotes rice yield and soil C, N stocks by increasing stability of macroaggregate and its associated C, N allocations in reddish paddy fields

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**ABSTRACT**

Rice straw biochar (RSB) and milk vetch (MV) are increasingly served as ideal soil amendments in promoting rice production and soil health in paddy fields. However, the mechanism of how annually applying RSB and MV, along with reduced N fertilizer, influenced rice productivity and soil carbon (C), nitrogen (N) stocks are elusive. A field experiment, with four treatments: 100% N fertilizer (N100), 80% N fertilizer along with RSB (N80B), MV (N80M), RSB+MV (N80BM) respectively, was conducted to evaluate the impacts on rice performances, soil aggregates and C, N stocks. Compared to N100 plots, N80B, N80M and N80BM obtained more grain yields, straw and shoot biomasses, and especially, the N80BM strikingly increased these items by 11.2%, 10.0% and 10.6%, respectively. The highest soil C, N stock rates were observed in N80BM, then soil organic C (SOCs) and total N stocks (TNs) were 5.42% and 6.92% higher than N100. Moreover, RSB and/or MV along with reduced N fertilizer prominently increased the mean weight diameter, geometric mean diameter and contents of aggregates at >0.25 mm by 7.14%-15.7%, 29.3%-58.1% and 7.92%-11.8%, while decreased content of silt-clay particle by 39.6%-62.9% vs N100 plots, respectively. The enrichments of C and N were mainly obtained in mega- and macro-aggregates, leading to noticeably enhancing the contents and contribution rates of aggregate-associated C, N at >0.25 mm in RSB and/or MV plots, and N80BM amplified these benefits. Pearson correlation analysis revealed dramatical positive relations among rice yield, TNs, SOCs and soil aggregate stability, and random forest model further explained 49.6%-75.9% of variations for rice yield, SOCs and TNs. Hence, results indicated that combining RSB with MV along with reduced N fertilizer is a promising strategy in promoting rice productivity, soil health, and greenhouse gas emission risks reduction, which have great potential in covering the food security and “dual carbon” objectives in China.

**Keywords:** straw biochar; green manure; soil aggregate; rice yield; soil C and N stocks

**Acknowledgments**

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# Microbiomes hold the key to build up high soil fertility beyond organic fertilization

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**ABSTRACT**

Organic fertilizers can partly substitute mineral fertilizers in addressing land degradation challenges, through their effectiveness varies by type. A global-scale meta-analysis of 422 pairs field experiments revealed that animal manure increases soil fertility more effectively than plant residues, especially on acidic ones. This difference is largely attributed to the greater microbial growth and activity stimulated by animal manure. Microorganisms, as one of the most abundant biological and functional groups on Earth, are increasingly use as innovatory productive forces in organic wastes utilization. For example, Acinetobacter and Aspergillus niger have been identified as high-efficiency bioinoculants that accelerate the composting of plant residues such as straw. They enhance organic matter degradation and nutrients (e.g., phosphorus) release, thereby narrowing the gap in soil fertility increases between applications of plant residues and of animal manure. A 45-day pot experiment demonstrated that combining straw with these microorganisms increased ryegrass (Lolium perenne L.) growth by 79.7% and phosphorus uptake by 102.5%. Furthermore, we also found some copiotrophic manure-borne bacteria can colonize soils for several months and improve nutrient cycling by regulating enzymatic stoichiometry. Cytophaga, as one of them, survives in 7 types of soils irrespective of manure application amount and frequency. Its colonization relies on the superior competition driving by interspecies antagonism over resident soil microorganisms. Together with novel perspective of “community coalescence” by which positively affecting ecosystem functions, engineering tailored microbial consortia for different organic fertilizers is expected to leverage microbiomes to promote sustainable agriculture.

# Size – Specific Effects of Intra-Aggregate Pore Size Distribution on Soil Aggregate Stability

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**ABSTRACT**

Soil aggregate stability is crucial for maintaining soil structural integrity and biochemical functions. However, the mechanisms by which intra-aggregate pore size distribution (PSD) influences stability across different aggregate size classes remain unclear. We measured intra-aggregate pore volumes using mercury intrusion porosimetry (MIP) and quantified aggregate water stability using the percentage of aggregate destruction (PAD) in 2–5, 1–2, and 0.25–1 mm aggregates collected from Mollisols after 0, 30, 60, and 90 years of traditional cultivation in Northeast China. We further evaluated the relative contributions of PSD, soil organic carbon (SOC), and soil texture (ST) to aggregate stability. The results showed that: (1) volumes of intra-aggregate pores decreased with increasing cultivation duration; (2) PAD increased from 0 to 30 years and then declined from 30 to 90 years; (3) pores in the 5–90 μm range were significantly negatively correlated with PAD across aggregate sizes, underscoring their pivotal role in maintaining aggregate stability; and (4) PLS-SEM analysis revealed that PSD was the primary driver of stability in M-sized aggregates, whereas SOC fractions were more influential in the other size classes. These findings provide mechanistic insights into soil structure and aggregate stability and may inform assessments of soil degradation, development of restoration strategies, and overall soil health.

# Spatial heterogeneity shapes enantioselective horizontal transfer of antibiotic resistance genes by pydiflumetofen in agricultural soils

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**ABSTRACT**

Chiral pesticides are widely used in agriculture, yet their enantioselective impacts on antibiotic resistance gene (ARG) dissemination under spatially heterogeneous soil conditions remain unclear. Here, pydiflumetofen (PYD), a newly introduced chiral amide fungicide, was selected to investigate how its enantiomers regulate ARG horizontal transfer in farmland soils. A cluster-resolved soil microcosm mimicking heterogeneous pesticide distribution during field application was coupled with microfluidic in situ observations plus an intergeneric conjugation model to quantify enantioselective effects and mechanisms. PYD exposure induced a non-monotonic risk pattern, as total ARGs, mobile genetic elements (MGEs), and the health-risk index peaked in the intermediate-exposure band (Cluster 2) rather than in the highest-exposure band, suggesting that risk may not increase linearly with concentration. Compared with S-PYD, R-PYD more strongly enriched multidrug resistance–associated ARGs and increased ARG–MGE network connectivity within the identified hotspot, indicating higher dissemination potential. Microfluidic assays further confirmed that conjugation predominantly occurred at biofilm interfaces on microstructured surfaces and reached its maximum under intermediate exposure. Mechanistically, PYD enantiomers differentially promoted bacterial attachment and biofilm development while eliciting stronger oxidative stress and metabolic responses, collectively enhancing conjugation frequency. These findings demonstrate that spatial heterogeneity can markedly amplify enantiomer driven ARG transfer by PYD, providing a basis for spatially explicit risk assessment and safer management of chiral pesticide use in agricultural systems.

**Keywords:**chiral pesticides, antibiotic resistance genes (ARGs), enantioselectivity, horizontal gene transfer, spatial heterogeneity

# Effects of Increased Temperature, Elevated $CO_2$ Concentrations and Drought on Soil Structure and Gas Diffusion in a Submontane Grassland Soil.

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**ABSTRACT**

Global climate change, driven by rising atmospheric $CO_2$ concentrations, is increasing the frequency and duration of extreme weather events, such as droughts and heavy rainfalls. The implications of these changes for soil-plant interactions in managed grasslands remain poorly understood. To investigate the combined effects of increased $CO_2$ (+300 ppm) and elevated temperature (+3 °C), along with a 2-month summer drought, we conducted a study using undisturbed topsoil and subsoil samples from a 10-year climate change experiment (ClimGrass) in a submontane grassland in Gumpenstein, Austria. We hypothesize that elevated $CO_2$ and temperature will enhance above- and below-ground biomass, leading to increased root growth and a corresponding rise in soil porosity, particularly of the proportion of biogenic macropores, which is expected improve aeration and boost gas diffusion rates.

We analyzed potential changes in soil structure by scanning 66 undisturbed samples with a high-resolution x-ray computed tomography system (only topsoil). Additionally, we measured water retention curves and oxygen diffusion rates (single chamber method) at different matric potentials (- 60, - 150, - 300 hPa) for the topsoil and subsoil, to examine how potential changes in total porosity, pore size distribution and pore connectivity affect gas exchange from the soil to the atmosphere at different moisture levels. As was expected, first results indicate that elevated $CO_2$ led to a lower bulk density and a higher amount of macropores, which also caused gas diffusion rates to increase. The moderating effects of elevated temperatures and droughts will also be discussed.

**Keywords:** Soil Structure, Water retention, Gas diffusion, Computed Tomography

# Evolution of SRO Fe oxides in soils along a paddy field chronosequence: A Fe isotope perspective

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**ABSTRACT**

Short-range-ordered (SRO) Fe oxides are highly reactive carriers for inorganic contaminants and key stabilizers of soil organic carbon, yet their formation and evolution under sustained redox oscillations in field soils remain poorly constrained. Here we track the evolution of SRO Fe oxides along a paddy soil chronosequence developed on Quaternary red clays by combining Fe stable isotopes, chemical extractions, and $^{57}$Fe Mössbauer spectroscopy. Mössbauer spectra and extractions show that paddy cultivation redistributes Fe from crystalline Fe oxides into SRO Fe phases, increasing the SRO Fe fraction in both short- and long-term paddy surface horizons and in deep horizons of the long-term paddy profile. Positive Fe isotope fractionation between soils and porewaters ($\Delta^{56}$Fesolid–porewater = 0.45–0.98‰) indicates systematic enrichment of heavy Fe in newly formed SRO Fe. In long-term paddy surface horizons, comparatively smaller $\Delta^{56}$Fesolid–porewater (0.45–0.79‰) together with similar $\Delta^{56}$Fesolid–colloid (0.35–0.91‰) point to a major contribution of ligand-complexed colloidal Fe on the precipitation of SRO Fe. In deeper horizons, larger $\Delta^{56}$Fesolid–porewater (0.73–0.98‰) consistent with $\Delta^{56}$Fesolid–aq (0.73–1.13‰) instead reflect direct reprecipitation of SRO Fe from a light, truly dissolved Fe pool. By integrating our data with published soil and wetland datasets, we identify a negative relationship between $\Delta^{56}$Fesolid–porewater and SRO Fe abundance across systems, with less positive fractionation associated with higher SRO Fe contents. These results demonstrate that Fe isotope fractionation, when coupled with spectroscopic and extraction-based approaches, is an effective tracer of SRO Fe formation and evolution in redox-dynamic soils, with implications for predicting soil carbon stabilization.

# Assessing Soil Function Loss in Traditional Gold Mining Landscapes UsingFunction-Based Soil Quality Indicator Models

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**ABSTRACT**

Traditional gold mining (TGM) can significantly contribute to land degradation, but its specific effects on vital soil functions remain underexplored in many developing regions. This study investigated soil degradation caused by TGM in Tigray, Ethiopia, with objectives to: (1) identify sensitive soil quality indicators and use them to develop function-based Soil Quality Indices (SQI); (2) compare two nonlinear scoring methods, threshold-based and mean-based; and (3) assess the extent of degradation caused by TGM across different sites.

A total of 192 soil samples were collected from various slope positions, depths (0–30 cm, 30–60 cm), and land uses (mined vs. unmined) at three TGM-affected locations. Out of 30 potential indicators, 11 were selected through principal component analysis to represent buffering and detoxification, nutrient cycling, structural stability & erosion resistance, and water–air–solute movement soil functions. SQI scores showed clear declines in soil function due to mining, especially on upper slopes and deeper layers. Over 52% of mined soils were classified as very low SQI grades, with degradation indices reaching up to 80% in upper slopes. Significant impacts included heavy metal buildup (Hg, Cu, Fe), nutrient loss (CEC, $Mg^{2+}$, P), and poor soil structure & erosion resistance, explained by low mean weight diameter and SOC, along with imbalanced water-solute-air movement caused by high soil compaction, low moisture content, and dominant coarse texture in the mined soils. The threshold-based scoring method proved more sensitive (sensitivity index: 16.03) than the mean-based approach (5.07), more effectively identifying soil degradation patterns. These findings confirm that function-based SQIs are significant for monitoring TGM-related soil impacts and the importance of slope-specific post-mining restoration strategies. Combining SQI data with land management plans and emphasizing the threshold-based approach are recommended.

**Key words:** Detoxification, Erosion tolerance, Nutrient cycling, Structural stability, Soil quality grades

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# Pore-Scale Insights into Water-Heat Coupling during Soil Thawing in the Black Soil Zone

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**ABSTRACT**

Soil thawing is a complex multiphysics process governed by pore-scale heat–water transport pathways. Long-term tillage practices fundamentally reshape soil pore networks, yet how such structural alterations influence thaw progression at the pore scale remains insufficiently understood. To address this gap, we investigated two contrasting systems—No-Tillage (NT) and Ridge Tillage (RT)—by coupling X-ray computed tomography (CT)-derived pore geometries with enthalpy-based Lattice Boltzmann Method (LBM) simulations to explicitly resolve transient heat transfer, phase change, and meltwater flow. Simulation results reveal pronounced differences in thaw behavior between the two pore architectures. RT exhibits accelerated thaw progression, with liquid saturation increasing to approximately 0.27, compared with about 0.12 in NT over the same duration. Vertical temperature profiles indicate that rapid phase conversion in RT facilitates deeper heat penetration, whereas NT maintains a sharp near-surface thermal gradient due to the high latent heat demand associated with its denser pore matrix. Three-dimensional diagnostics further show that interconnected macropores in RT sustain buoyancy-driven meltwater convection, enhancing downward heat transport beyond purely conductive limits. In contrast, flow fields in NT remain weak and spatially confined, restricting heat transfer to slower conductive pathways. These results reveal that soil thawing is jointly controlled by local ice–water–solid phase configurations and tillage-induced pore topology, among which the ice–water–solid phase configurations govern latent heat consumption during melting, whereas the pore topology regulates heat redistribution through conductive and convective pathways. This pore-scale perspective provides a physical basis for observed variability in field-scale thaw rates and offers quantitative constraints for improving the representation of freeze–thaw processes in land-surface and agrohydrological models.

# Nonstationary response evolutionary mechanisms of aggregate binding agents in Quaternary red soils during 400 years of cultivation

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## ABSTRACT

Understanding the aggregate evolution of Quaternary red soil (QRS) is critical for its rational utilization. Despite its importance, the regulatory mechanisms governing interactions between soil organic matter (SOM) and Fe oxides during QRS aggregate formation remain unclear. Here, the QRS pedons cultivated for 0, 5, 80, and 400 years were systematically investigated. A QRS chronological framework was then established by determining the uniformity of parent material and the reliability of relative age. Using a soil reconstruction approach, the temporal evolution of SOM, poorly crystalline iron oxides (Feo), crystalline iron oxides (Fec), and aggregate structure across cultivation periods were quantitatively analyzed. Results revealed nonstationary responses of SOM and Fe oxides to cultivation duration. With cultivation time, SOM content initially decreased (0.01–0.03 g 100 cm–3 at 5 years) before increasing (0.04–0.11 g 100 cm–3 at 80 and 400 years). While, Fe oxides exhibited inverse trends—initial increases (0.20–0.85 g 100 cm–3 at 5 and 80 years) followed by decreases (0.09–0.33 g 100 cm–3 at 400 years). The critical time threshold for organic/inorganic binding agent evolution was identified, and cultivated QRS aggregate formation was divided into three stages. Stage I (0–6 years): Fe oxides dominate as primary binding agents. Stage II (6–362 years): Co-dominance of Fe oxides and SOM. Stage III (>362 years): SOM replaces Fe oxides as principal binding agents. Under these temporal dynamics, aggregate progression occurred in both arable and argic horizons, though aggregation rates declined with cultivation time. In arable horizons, <0.053 mm silt and clay fractions (7.89–14.24 g 100 cm–3) continuously bound to 0.5–1 mm macroaggregates (13.26–21.32 g 100 cm–3), while 0.25–0.5 mm macroaggregates fragmented (3.73–15.18 g 100 cm–3). In argic horizons, macroaggregate size distributions shifted toward 2–5 mm (upper horizons, 26.36–28.26 g 100 cm–3) and 1–2 mm (middle-lower horizons, 11.45–22.65 g 100 cm–3) after 6 years. These findings elucidate the nonstationary mechanisms of aggregate formation in response to organic-inorganic binding agent evolution and provide novel chronological evidence to refine aggregate formation theories in soil science. The identified temporal thresholds and stage transitions offer critical insights for sustainable QRS management and soil classification frameworks.

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# Drivers of nitrification in surface soils of Oxisols and Ultisols in tropical forests of the Central Highlands, Vietnam

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**ABSTRACT**

Higher nitrate ($NO_3^-$) fluxes have frequently been observed in Oxisols than in Ultisols of tropical forests (Shibata et al., 2017), yet the mechanisms underlying this pattern remain poorly understood, particularly in Southeast Asia where both soil types often exhibit similarly strong acidity. Field-based flux measurements alone provide limited insight into the processes governing nitrogen transformations. This study therefore examined the controls on nitrification and $NO_3^-$ dynamics by directly comparing surface soils (0–5 cm) of Oxisols and Ultisols developed under comparable climatic and vegetation conditions in tropical forests of the Central Highlands, Vietnam. Surface soils from 10 Oxisol and 8 Ultisol sites were analyzed for physicochemical properties, soil aggregate size distribution, microbial community characteristics, and nitrogen transformation processes. Gross nitrification rates were determined using a 15N tracer incubation method. The abundance of ammonia-oxidizing archaea (AOA) and bacteria (AOB) was quantified by real-time PCR, and stable nitrogen isotope ratios (δ15N) of soils and litters were measured to infer dominant nitrogen loss pathways. Gross nitrification rates and gross $NO_3^-$ consumption rates tended to be higher in Oxisols than in Ultisols, although the differences were not statistically significant. Rate constants of gross nitrification did not differ between soil types, suggesting that observed variations in nitrification activity were largely attributable to differences in substrate availability rather than inherent soil-type effects. Oxisols exhibited significantly higher clay contents, accompanied by greater organic matter accumulation and higher $NH_4^+$ availability. Correspondingly, the abundance of AOA was significantly greater in Oxisols and showed strong positive correlations with total carbon, total nitrogen, and $NO_3^-$ concentrations, whereas AOB abundance was consistently low across both soil types. Soil physical structure further distinguished the two soil types. Oxisols were characterized by smaller mean weight diameters and higher proportions of 0.25–2 mm aggregates. This aggregate fraction was positively associated with AOA abundance, indicating that microscale physical environments, likely through enhanced aeration and permeability, contribute to favorable conditions for nitrification. Stable isotope signatures suggested that denitrification played a more important role in $NO_3^-$ consumption in Ultisols, whereas leaching losses were likely more pronounced in Oxisols. Taken together, these results indicate that enhanced $NO_3^-$ fluxes in Oxisols are regulated by an interplay of substrate supply, soil physical structure, and microbial community composition rather than soil type per se. The findings emphasize the importance of integrating biological and physical controls when interpreting nitrogen flux patterns in highly weathered tropical forest soils.

**Acknowledgments**

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# Deep soil nitrate accumulation depends on the regolith structure and surface land management

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**ABSTRACT**

Deep nitrate accumulation below 1 m threatens groundwater quality, yet studies predominantly focus on surface soils (<100 cm) or specific sites, lacking large-scale cross-regional comparisons. This study investigates the distribution and controls of deep nitrate accumulation across two critical agricultural zones: highly weathered subtropical red soils and the intensively managed black soil (Phaeozems and Chernozems) region of Northeast China, where such accumulation was previously undocumented. We analyzed inorganic nitrogen forms and regolith properties in multiple deep boreholes (up to 10 m in black soil sites; encompassing full regolith profiles in red soils) spanning climatic gradients (humid to semi-arid) and management histories (e.g., planting years of orchard/cropland).

Results reveal significant but distinct deep nitrate accumulation patterns. In the black soil region, substantial nitrate accumulation was found specifically in the semi-arid site (Lindian), peaking at 11.03 mg N $kg^{-1}$ at 3 m depth, with 70% of the large storage (459.65–1072.88 kg N $ha^{-1}$ to 10 m depth) located below 1 m. In contrast, the red soil region showed storage from 43.6 to 1116.3 kg $ha^{-1}$ within the weathered regolith, where 81% of nitrate was stored in reticulated red clay layers. A key finding across both regions is that deep nitrate accumulation is governed by the interplay between subsurface regolith structure (e.g., thickness, texture, clay layers) and surface processes (e.g., land use history, fertilization, hydrological pathways). In red soils, regolith thickness strongly correlated with nitrate storage ($R^2$=0.43), and all accumulation parameters (except peak depth) increased with planting years. In black soils, regolith properties (clay, silt, sand, pH) were crucial in reshaping nitrate vertical patterns, with notable spatial variability: one site showed deep ammonium instead of nitrate accumulation, and another showed no accumulation, highlighting climate-management-regolith interactions.

We conclude that the paradigm of surface-focused nitrate management is insufficient. The presence of deep nitrate pools, whether in the reticulated clay of red soils or the subsoil of black soils, necessitates a regolith-centric perspective. Identifying regions vulnerable to high accumulation requires understanding how local management interacts with the specific deep regolith architecture and climatic context to mitigate groundwater pollution risks.(Yang et al., 2020a; Yang et al., 2020b; Yang et al., 2024; Yang et al., 2026)

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# Pore-Scale Structural Regulation of Soil Carbon Mineralization during the Corn Growing Season in a Yellow-Brown Soil

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**ABSTRACT**

Soil carbon sequestration is essential for maintaining soil fertility in agricultural systems and mitigating climate change. Soil pore structure could regulate soil carbon mineralization by controlling gas diffusion and the physical accessibility of organic substrates within the soil matrix. However, the mechanistic links between the temporal and spatial dynamics of soil pore structure and soil carbon emissions remain insufficiently understood, limiting the development of effective soil management strategies for sustainable agroecosystems. The objective of this study is to elucidate how temporal and vertical variations in pore-scale soil structure regulate soil carbon mineralization in a corn cropping system developed on yellow-brown soil in Anhui Province, China. We quantified three-dimensional soil pore structure characteristics, including pore size distribution, connectivity and spatial heterogeneity across key corn growth stages and soil depths using X-ray computed tomography combined with digital image analysis and geostatistical methods. Soil carbon mineralization rates were measured concurrently to assess their relationships with dynamic structural attributes. The results reveal pronounced seasonal and vertical variability in soil pore architecture during the corn growing season, with changes in pore connectivity, complexity and pore size distribution closely associated with variations in carbon mineralization rates. These findings demonstrate that dynamic pore-scale structural organization constitutes an important physical regulatory pathway linking soil structure to carbon cycling within the agricultural Critical Zone. This study advances a structure-based understanding of soil ecosystem functioning and provides a scientific basis for managing soil structure to regulate carbon emissions in agroecosystems.

**Keywords:** soil pore structure; spatiotemporal dynamics; soil carbon emission; carbon mineralization; agroecosystems

# Stabilizing Soil Aggregates with Synthetic Polymers: A Wet Adhesion Perspective

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**ABSTRACT**

Soil aggregates, as the fundamental structural units of soil, govern key soil functions through their formation, stabilization, and disintegration processes. Conventional understanding emphasizes the role of soil organic matter as a cementing agent that promotes soil aggregation, with aggregate stability largely attributed to this binding effect. However, existing research has primarily focused on interfacial interactions between soil particles and organic matter, overlooking the critical influence of the bulk properties of the binder—whether natural organic matter or synthetic polymers—on adhesion performance under wet conditions. From a materials science perspective, reliable wet adhesion requires two simultaneous criteria: strong interfacial interaction and sufficient mechanical toughness of the adhesive itself. Guided by wet adhesion design principles, this study re-examines the limited efficacy of common polymeric soil conditioners such as polyacrylamide (PAM), which suffers a drastic loss of mechanical toughness upon water uptake and thus fails to sustain long-term adhesion. We propose polyvinyl alcohol (PVA) as a superior polymeric binder. PVA not only forms strong hydrogen bonds with aluminosilicate mineral surfaces but also develops crystalline domains during drying, significantly enhancing its mechanical toughness. This synergistic mechanism—combining high interfacial energy with high bulk toughness—enables PVA to effectively bridge soil particles and construct highly stable aggregates. Experiments show that PVA-stabilized soil aggregates remain intact after one year of use under pot-culture conditions, with no observable disintegration (Figure 1), demonstrating significantly greater stabilizing efficiency than PAM. The resulting PVA-treated soil can be directly used as a potting medium, offering a sustainable alternative to non-renewable peat and reducing reliance on its extraction. Moreover, it holds promise for engineered soil structure management, as it enables direct control over aggregate size and distribution through machine-based fabrication. By integrating principles from materials science and soil science, this work presents an innovative paradigm for soil structure design and degraded land restoration.



Figure 1. PVA-treated soil aggregates remain intact after one year in pot culture, with no disintegration evident.

# Spatial distribution and influencing factors of the argillic horizon in the Northeast Black Soil Region

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**ABSTRACT**

The argillic horizon serves as a critical structural support and hydrological regulator within soil profiles in Northeast China's Black Soil Region, with its spatial distribution profoundly influencing the productivity and ecological functions of black soil. This study aims to elucidate the spatial distribution characteristics of the argillic horizon in Northeast China's black soil region and quantitatively analyze its dominant environmental drivers. By integrating field survey sampling data and the historical soil survey data from 852 soil profile samples, combined with high-resolution environmental covariates (climate, topography, parent material, etc.), a random forest model was applied to predict the spatial distribution and characteristics of the argillic horizon.

Results indicate:The occurrence areas of the horizon were defined, primarily distributed in Jiamusi City, Harbin City, and Jixi City in Heilongjiang Province; Jilin City, Liaoyuan City, and Tonghua City in Jilin Province; Chaoyang City, Huludao City, and Dalian City in Liaoning Province; Chifeng City, Tongliao City, and Xing'an League in Inner Mongolia Autonomous Region. The total area of the horizon is approximately $14.7170\times10^4$ km², with distinct regional characteristics in its formation and distribution across different areas. Revealed the spatial distribution of the horizon characteristics: high-value depth zones are primarily concentrated in central-eastern Heilongjiang Province, central Jilin Province, and northeastern Liaoning Province, while low-value zones are mainly distributed in the southern part of the Eastern Four Leagues of Inner Mongolia and western Liaoning Province. High-value burial thickness zones are mainly concentrated in eastern Liaoning Province, while low-value zones are primarily distributed in the southern part of the Eastern Four Leagues of Inner Mongolia and northeastern Heilongjiang Province.

It clarifies that the formation of the horizon is influenced by multiple factors. Under the combined effects of climate, soil type, topography, biological factors, and parent material, the characteristics of the horizon exhibit distinct regional patterns across different areas. In areas with favorable climates and deep parent material, the horizon is thick; conversely, in regions such as shoulder slopes, steep slopes, and eroded terrace margins with harsh climatic conditions, the horizon is thin. This demonstrates the complexity and diversity of the horizon formation mechanism.

**Acknowledgments**

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# Soil aggregate stability index independent from pre-stress aggregate size distribution: A test from soils affected by the water level fluctuation in the Three Gorges Reservoir, China

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**ABSTRACT**

Soil aggregate stability measurement is essential to determine soil health status under various conditions. The Mean Weight Diameter (MWD) is the most applied index to express aggregate stability particularly for wet and dry sieving. However, the MWD could generally present results affected by pre-stress aggregate size distribution when remained aggregates after stress are considered for calculation. Therefore, the objective of the present study was to eliminate the similarities between the MWD results and pre-stress aggregate size distribution, which largely affects treatments differentiation. Samples from 145-160 m (lower), 160–169 m (middle), and 169–175 m (upper) elevations differently affected by the Water Level Fluctuation in Three Gorges Reservoir (TGR) and control (>175 m) were exposed to wet shaking stress. Aggregates remained at each sieve opening, aggregates disintegrated/passed through the sieve opening, and small macroaggregates and microaggregates accumulated were recorded. These aggregates were used to determine and compare two indexes (1) using remained aggregates (MWD) and (2) using disintegrated/accumulated aggregates (MWDd/a) based on the differences among treatments. The results for both pre-stress aggregates and remained aggregates after stress were showed consistent significant differences ($p < 0.05$) between upper and control elevations. This gives indication that aggregates remained after stress strongly depend on pre-stress aggregate size distribution. As the MWD was calculated from remained aggregates, the identified difference between upper and control elevations for this index could also confirm its dependence to pre-stress aggregates distribution. Contrary, disintegrated and accumulated aggregates showed non-significant differences between upper and control elevations. This non-significant and significant differences between upper and control elevations for disintegrated and pre-stress aggregates suggest a non-dependence condition. Similarly, the upper and control elevations showed no significant differences in MWDd/a. This substantially informs that this index is independent from pre-stress aggregates distribution because it was entirely calculated from disintegrated aggregates. Higher aggregate stability was indicated by high MWD, with values ranging from 1.41 to 6.24 mm. On the other hand, higher stability was expressed by lower values of the MWDd/a, with the values varying between 3.87 and 0.5 mm. Overall, the present study evidenced the major advantage of considering the disintegrated/accumulated than remained aggregates in calculating unbiased MWD index for aggregate stability.

# What Are Skeletans and How Do They Form?

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**ABSTRACT**

Skeletans are defined in the USDA Glossary of Terms Used in Soil Survey and Soil Classification as a specific type of ped and void surface feature consisting of clean sand or silt coatings. These features may form through removal of clay, silt, organic matter, and iron oxides from specific sites, leaving the immobile sand and silt particles behind. Although sand grains are unlikely to be translocated in soil, some silt skeletans may be formed by translocating silt particles onto ped and void surfaces. Skeletans are referred to in the 13th Ed. of the Keys to Soil Taxonomy in various ways. They are listed as clay depletions (a type of redoximorphic feature), as diagnostic criteria for seven great groups and eight subgroups where saturation and reduction are not implied, as tongues of albic material, interfingering of albic material, coatings of albic materials, or uncoated sand and silt grains in multiple places. The definitions of skeletans in the literature are variable as are the processes mentioned in their formation. The processes may include eluviation-illuviation, oxidation-reduction, gleization, lessivage, chelation, and ferrolysis. The presence of albic materials and skeletans are diagnostic criteria in both the World References Base for retic properties and albeluvic glossae in natric, argic, and fragic horizons and in US Soil Taxonomy classification systems for glossic horizons. A literature review on the formation of tongues of albic materials and skeletans will be presented.

# Abundance of Luvisols, Retisols and accompanying 'glossic' soils in NE Poland. Ecological implications

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**ABSTRACT**

The western range of Albeluvisols on soil maps of Europe abruptly ends at the border between Poland and Belarus, as albeluvial tonguing has not been identified in Poland at any classification level (till 2011). The third edition of WRB (2014) replaced Albeluvisols with Retisols and allowed tonguing (as retic/glossic properties) in Planosols and Stagnosols, which precede Retisols (and Luvisols) in the key to References Soil Groups (RSGs) of the WRB. This change is expected to have complicated the deciphering of the transition of Albeluvisols/Retisols to Luvisols in Poland and surrounding countries. A set of 166 forest soil profiles with Bt horizons in NE Poland, just at the border with Belarus, was analysed to approximate the abundance of tonguing (retic/glossic) in the Bt horizons, to establish classification of these soils in terms of the 4th edition of WRB (2022) and to describe the relationships between RSGs and forest vegetation, the latter identified as phytosociological plant communities.

The soils were developed from glacial till and cover sands on till, thus commonly having a lithic discontinuity (sand/loam) at a depth of 30-90 cm. Only 22% soils had argic Bt horizons, not accompanied by tonguing and stagnic properties; thus, they were classified as Luvisols. The other 78% were characterised by tonguing in the upper section of Bt horizon; however, only 30% belonged to Retisols, while 12% to 36% to Retic Planosols and Retic Stagnosols. The mentioned RSGs do not form large spatial clusters, but are scattered in a mosaic pattern, typically for the transition zone.

Among the identified plant communities, Tilio-Carpinetum (T-C) caricetosum remotae and T-C circetum alpinae occurred nearly exclusively on Planosols and Stagnosols; whereas, T-C typicum and T-C stachyetosum dominated on Retisols followed by Luvisols, while T-C melittetosum and T-C calamagrostietosum – on Luvisols followed by Retisols.

Data from NE Poland showed that the priority given to stagnic over retic properties, and the respective splitting of Albeluvisols among Planosols, Stagnosols, and Retisols as in WRB 2014 and 2022, better reflects the ecological relationships than merging all soils with albeluvial tonguing into one RSG, as it was in WRB 1998 and 2006. Furthermore, forest vegetation does not differ significantly on Retisols and Luvisols, indicating a small impact of tonguing on the ecological status of well-drained soils.

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# Still Soil or Already Sediments: Boundary Cases with Ferrugination in Russian Nature Reserves (Smolensk Lakelike and Geyzer Valley)

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**ABSTRACT**

In the Smolensk Lakelike National Park (NW Russia), due to plowing, the upper horizons of sandy soils (Albic Podzols and Albic Arenosols) are homogenized, and the remaining brown layer underling the Ap horizon is barely distinguishable—this is the lower part of the spodic horizon or parent material with a specific color (fig. 1). The situation is complicated by the fact that some local lacustrine sediments are very similar in color to the spodic horizon of Podzols. During field observation, how can determine whether this is the remnants of a soil horizon or parent material? Which laboratory tests can help to separate B and C horizons in this case?

Another diagnostic challenge is the presence of bands in the lower part of these soils that do not resemble ortsands or pseudofibers (fig. 1B). In some similar soils, a cemented, brown sand layer occurs. How can we determine whether there are the results of soil processes or geological ones?

In the Geyzer Valley and worldwide, whenever there is the influence of steam-heated acid-sulfate waters, specific soils form. They have temperature ≥ 50 C at a depth of 50 cm, bright Munsell color in moist state (hue ≥ 5R, value ≥ 3, chroma 6 –8), loamy texture or finer, mineral composition dominated by kaolinite, a fluidal micro texture in reflected light (Munsell color; hue ≥ 5R, value 2.5–4, chroma 4–8). Это всё еще почва? Или геологическое образование? Если почва, то следует для нее вводить специфические критерии?

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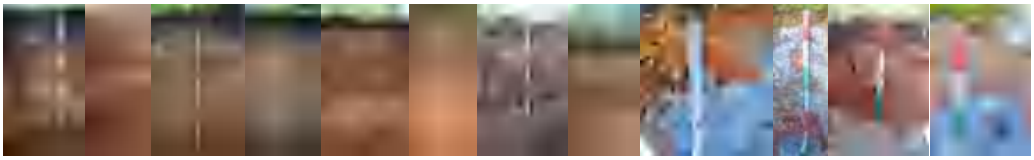


Figure 1. Obstacle examples of soils for diagnostics. Upper raw: plowing soils with brown subsoil under the Ap horizon. Middle raw: soils with ferruginized bands. Lower raw: ferruginized soils effected by steam-heated acid-sulfate waters.

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# Mattic epipedon: living skin of the Tibetan Plateau

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## ABSTRACT

The Kobresia pastures on the Qinghai-Tibetan Plateau (QTP) are a key feature of the world's largest alpine ecosystem (1). They occupy approximately 450,000 km2, nearly 1/5 of the area of the QTP, and dominate the headwaters of most of Asia's great rivers. Kobresia plants are typically only a few centimeters tall and form a fairly firm turf blanketing all relief positions wherever the environment allows (2, 3). The Kobresia roots are interwoven with the surface soil. This characteristic layer is called a "mattic epipedon—a mat-like surface soil layer," according to Chinese soil taxonomy. This definition is not found in other soil classification systems, but has been adopted in China primarily as a diagnostic feature for alpine meadow soils.

The occurrence of the mattic layer is fundamental to the life system there. The humble primary production feeds all animals, wild and domesticated, which in turn sustain human life and the biodiversity of the vast, yet so far pristine, land. Without this thin skin, the ecosystem is doomed to collapse. While substantial advances have been made in elucidating the vegetational and ecological underpinnings, eco-hydrological functions, and degradation processes with associated ecological risks of these life-sustaining turfs, their formation mechanism remains unresolved.

In this work, we sampled 74 turf mat profiles across Kobresia-dominated landscapes, and integrated data from 42 published sites. We analyzed grain-size distributions to trace sediment provenance and employed luminescence dating to determine the onset of turf layer development. By relating spatiotemporal pattern of turf evolution to regional climate dynamics and quantitative grazing intensity, we assessed turf mat resilience to environmental change and long-term grazing. Our findings provide unprecedented insights into formation mechanisms, spatiotemporal evolution, and resilience of this crucial, unique and prevalent system.

crossed, an irreversible shift to barren conditions can occur abruptly.




Figure 1. Turf landscape in various geological settings. (A) Turfs over clastic debris. (B) Turfs over substrates of diverse geology. (C) Turfs over buried topsoil horizon.

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# The Umbrisol problem

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**ABSTRACT**

According to the WRB concept, Umbrisols are characterized by the presence of deep, dark and organic-matter rich Umbric topsoil diagnostic horizons, the acidic counterpart of soils with Mollic horizons such as Phaeozems, Chernozems and Kastanozems. Their high C stocks make them particularly important for C sequestration in terrestrial environments. They mostly develop in humid mountain areas, both temperate and tropical , usually on silicatic or volcanic bedrocks, and only rarely on limestone or dolostone. However, their known distribution is underestimated, as older classification systems referred to them in different ways, often associating them with soil types corresponding to Cambisols, Luvisols or Regosols. For example, Umbrisol distribution maps at the global and European scales do not show their extensive presence in the southern European Alps, where they are the most common soil type on south-facing slopes on silicatic bedrocks and sometimes even on limestone or dolostone.

Despite their similarities to non-acidic Phaeozems, the genesis of Umbrisols is very different, as is the vegetation under which they are often found. In fact, soils with Mollic horizons are usually associated wih grasslands, with which they are genetically linked, whereas soils with Umbric horizons are often found under broadleaf forests.

Also today, however, many different views exist regarding their genesis and classification. Many soils usually classified as Umbrisols have andic or protoandic properties, and they have been sometimes classified by different soil scientists also as Andisols (e.g. in NW Spain). In other cases (Southern Switzerland and NW Spain), the increasing root density and the darker colour of subsurface horizons compared to the uppermost Ah has been interpreted as evidence of podzolization, and these soils have been termed "cryptopodzols" . The widespread black lower part of the Umbric horizon has also been interpreted as a buried Ah (e.g. NW Spain). The presence of charcoal fragments derived from anthropic forest clearing has also been often observed and considered as one of the main factors controlling the stable organic matter and the dark colour. Large quantities of amorphous Fe and Al oxyhydroxides, however, characterize Umbrisols, and they usually grade into Podzols at higher elevations or on colder northward slopes. In many cases, the deep black section of the Umbric horizon below the roots does not show visible biological activity (coarse blocky subangular aggregation, very scarce pellets and monomorphic organic matter in thin section). These properties and the gradual lower boundary, which often seems to follow water percolation pathways, could be related to illuviation of organic acids, although definitive evidence is still lacking.

# Environmental factors influencing soil particle size distribution and their spatial distribution characteristics in the Tarim River Basin

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**ABSTRACT**

Soil particle size fractions directly influence soil texture, fertility, ecological functions, and agricultural production potential. This study, based on 383 soil layers from 107 typical soil profiles (0~100 cm) in the Tarim River Basin, analyzed the effects of environmental factors using non-parametric tests, correlation analysis, and random forest algorithms, and predicted their spatial distribution. The results indicate that: (1) The soil particle size fractions in the basin are dominated by sand and silt, with the proportions of sand, silt, and clay being 44.21 ± 25.12%, 45.26 ± 20.37%, and 10.51 ± 9.60%, respectively. Sand exhibits a highly significant negative correlation with both silt and clay, while silt and clay show a highly significant positive correlation. The soil formation process in the Tarim River Basin is weak, with relatively strong physical weathering and relatively weak chemical weathering. (2) Environmental variables such as geomorphology, soil type, sunshine duration, accumulated temperature, elevation, and evaporation significantly influence the spatial distribution of soil particle size fractions in the basin. Among these, geomorphology has the greatest impact, exceeding 20% across all soil layers, followed by soil type, which exceeds 10% in all layers. (3) In terms of vertical profile distribution, the proportion of sand in the 0~25 cm and 25~50 cm layers is relatively highest in the desert area, while it decreases in the 50~75 cm and 75~100 cm layers. The West Kunlun Mountains exhibit a high proportion of sand across all layers. The proportions of silt and clay in the 0~25 cm and 25~50 cm layers in the desert area are lower than those in the surrounding piedmont belt, while the opposite is observed in the 50~75 cm and 75~100 cm layers. (4) On a macro scale, the spatial distribution characteristics of soil particle size fractions in the basin are fundamentally controlled by the annular geomorphological pattern of "two mountains flanking a basin." This geomorphological pattern influences the spatial distribution of environmental factors such as soil parent material, soil type, and climate, thereby affecting the spatial distribution of particle size fractions. The findings of this study provide a basis for the precise management of soil resources in the basin and contribute to ensuring the sustainable development of oasis agriculture and ecological environment construction.

**Keywords:** Soil particle size distributions; Tarim River Basin; Spatial distribution; Environmental factors

**Acknowledgments**

This work is supported by the Third Xinjiang Comprehensive Scientific Survey Project - Land Resource Development and Agricultural Resource Survey in the Tarim River Basin (No. 2021xjkk0200).

# Technical Approaches and Practices for Assessing Agricultural Suitability of Soils in China

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**ABSTRACT**

Soils constitute a central component of the Earth's Critical Zone, and agricultural land is a strategic resource essential for ensuring national food security, maintaining ecological stability, and supporting rural revitalization. In the context of rising global food security challenges and increasing land-use constraints, scientifically assessing soil agricultural suitability is vital for shaping agricultural production patterns that align with natural geographical structures and agricultural production laws. Responding to the national food security strategy, this study develops a systematic, standardized, and scalable framework for soil agricultural suitability assessment based on the ongoing Third National Soil Survey of China. The framework is applied at the national scale and validated through full-process practice in representative pilot counties.

The study establishes a technical specification system encompassing an evaluation index system, classification standards, and mapping procedures, and clarifies the hierarchical evaluation logic and deliverables from county to municipal and provincial levels. National-scale results show that climate- and landform-driven macro-geographical patterns largely determine the spatial boundaries and suitability grades of different agricultural land types. Significant regional differences are observed in the optimization potential and structural adjustment of cropland, forestland, and grassland, while the availability of effective reserve arable land remains limited, underscoring the need for refined spatial planning and strict protection. Validation in typical pilot counties demonstrates that the proposed framework is scientifically robust, operationally feasible, and capable of transforming soil survey data into practical decision-support products for cropland optimization and agricultural spatial restructuring. This provides a clear and implementable technical pathway for local agricultural land-use planning.

Overall, the research presents a comprehensive and scalable full-process solution for soil agricultural suitability assessment. It highlights the foundational and strategic value of nationwide soil survey data in supporting macro-level policy decisions, safeguarding agricultural productivity, and advancing sustainable agricultural development. The framework also offers a Referencesable model for countries or regions with large-scale agricultural production needs, providing scientifically grounded and practical pathways to alleviate human–land conflicts and enhance the efficiency of land resource allocation.

**Acknowledgments**

This study was supported by the Key Project of National Natural Science Foundation of China (No. 42430705)

# Standards and Protocols for Soil Spectral Reflectance to Enable Remote and Precision Soil Mapping

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**ABSTRACT**

Over 25 years, research groups worldwide have been actively involved in soil spectroscopy, measuring soil reflectance across the VIS–NIR–SWIR (0.4–2.5 µm) region, primarily for chemometric applications. This effort has led to the development of numerous soil spectral libraries (SSLs), ranging from local to continental scales, each employing different sensors and measurement protocols. Because soil is a dynamic and complex system influenced by a wide array of variables, even small changes can result in significant variations in its VIS–NIR–SWIR reflectance. Consequently, accurate soil reflectance measurements are critical, as they are highly sensitive to factors such as measurement geometry, illumination conditions, sensor characteristics, and sample preparation. As a result, merging or comparing SSLs measured under different conditions (e.g., sensors and environments) remains a major challenge. With the emergence of hyperspectral remote sensing (HSR) technologies—both airborne and spaceborne—SSLs are becoming increasingly valuable for direct implementation in HSR data analysis. For such applications to be effective, harmonized SSLs at the global scale are essential. To address this need, a group of soil spectroscopy and HSR scientists began collaborating in 2020 under the IEEE Standards Association Working Group P4005, focused on Standards and Protocols for Soil Spectroscopy. This effort is aligned with the GLOSOLAN-SPEC working group, which aims to develop a globally representative, harmonized soil spectral calibration library based on VNIR–SWIR–MIR spectra and corresponding soil property References data generated by a gold-standard References laboratory. The project examines how different protocols, sensors, and measurement methods can be harmonized to achieve global consistency among SSLs. This initiative is ongoing, and the P4005 Working Group has already released draft version #17 for both laboratory and field VNIR–SWIR measurements. The protocol is currently being finalized through comprehensive discussion sessions prior to approval by the IEEE NesCom Committee, which is expected to release the standard by the end of 2026. In this paper, we describe the benefits of the protocol's harmonization capabilities, introduce standardized procedures for measuring soil reflectance, and link the protocol to field spectral measurements.

**Importance of the project**

As many SSLs are now rapidly expanding (e.g., in China, where the goal is to sample over one million soils for the national SSL), it is essential that SSL developers adopt a common protocol to ensure a shared parameterization framework. This is particularly important because SSLs underpin a wide range of applications, including precision agriculture, from ground-based measurements to airborne and spaceborne observations.

# Building a National Soil Spectral Library from China's Third Soil Survey

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**ABSTRACT**

The Third Soil Survey of China (TSSC) has collected and preserved millions of soil samples under a consistent, high-quality protocol. This invaluable archive presents an unprecedented opportunity to construct a massive national soil spectral library. We are utilizing this resource to explore the diagnostic potential of soil spectroscopy for assessing soil conditions, determining soil classification, and predicting key soil properties, leveraging recent advances in artificial intelligence. Our systematic approach involves measuring three complementary spectral domains for each sample: visible and near-infrared (vis-NIR), mid-infrared (MIR), and X-ray fluorescence (XRF) spectroscopy. The integrated spectral data will serve as the foundation for a deep neural network model designed to be scalable for applications at various spatial levels. This initiative is critical to meeting the growing demands of precision agriculture, digital soil mapping, and soil remote sensing. Ultimately, this research aims to establish soil spectroscopy as a reliable and efficient alternative to conventional soil chemical analysis.

# The National Soil Archive of China

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**ABSTRACT**

Soil samples preserved for the long term represent a crucial component of national sci-tech infrastructure and hold significant value for research on long-term soil and environmental changes, as well as for open sharing of scientific data. In recent years, with the continuous increase in China's investment in agricultural and ecological environmental science and technology, the intensity of soil surveys has gradually expanded, and the accumulation rate of soil samples has noticeably accelerated. Consequently, there is an urgent need for relevant standards and guidelines to direct the long-term preservation of soil samples. The Third National Soil Survey serves as a "comprehensive physical examination" of China's soils, carrying epoch-making significance for both national condition surveys and scientific research. Establishing the Third National Soil Survey sample repository presents an excellent opportunity to create representative spatiotemporal snapshots of China's soils in the new era and systematically address the historical shortage of soil samples in the country. The implementation plan for the Third National Soil Survey clearly states that the sample repository is one of the primary outcomes of the survey, requiring the establishment of standardized and intelligent national and provincial soil sample repositories, along with typical soil profile specimen banks.

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# Soil Type Prediction Based on Soil Formation Factors and Random Forest

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This study focused on Huaping Town, Jianshi County, Hubei Province, China. A soil type prediction model was constructed by utilizing soil-forming environmental factors — including Climate (long-term monthly averages of precipitation, temperature, and potential evapotranspiration), Organisms (monthly Normalized Difference Vegetation Index), Topography (such as DEM, slope, valley depth), Parent Material, and Human Activities (land use) — in combination with Latin Hypercube Sampling and Random Forest algorithms. The model identified 31 soil types within the study area, achieving an overall prediction accuracy of 81.79% and the Kappa coefficient of 0.8. This demonstrated the method's effectiveness in supporting precise regional soil resource surveys and digital soil mapping, providing a reliable foundation for extending this approach to the entire county to generate a complete soil type classification result. The importance analysis of environmental factors further revealed the dominant mechanisms governing soil development and differentiation. Specifically, temperature and hydrological conditions served as the fundamental control, with moisture conditions in summer and autumn exerting a particularly significant influence. Topographic factors played dual roles in directly describing landforms and indirectly regulating the spatial distribution of temperature and hydrological conditions. Parent material types and human activities drove the local differentiation of specific soil types. Through both model predictions and mechanism analysis, this study validated the reliability and interpretability of the digital soil mapping method for identifying soil types in mountainous areas. The findings provide a scientific basis for refined soil resource management and land quality assessment.

# Construction of Hainan Soil Spectral Library Driven by Large Model and Mapping of Organic Matter at 30m Resolution

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**ABSTRACT**

Tropical regions have high temperatures and heavy rainfall, complex soil formation conditions, and highly heterogeneous soil physical and chemical properties and spectral responses. It is urgent to rely on large-scale measured sample points to construct a standardized soil spectral library and form high-resolution soil organic matter spatial distribution products to provide support for farmland management and soil quality assessment. This study is based on approximately 6000 soil samples and supporting physical and chemical data collected in Hainan Province, and constructs a tropical typical soil spectral database. A 30 meter resolution soil organic matter mapping framework driven by a large model is proposed.

In terms of database construction, in response to the characteristics of high dimensionality, large volume, and frequent updates of spectral data, the VIS-NIR spectra of soil samples and 18 physical and chemical indicators are encoded and stored under a unified primary key. Introduce column based storage and wavelength band indexing for spectral curves to achieve fast retrieval based on wavelength ranges, soil types, and other conditions. Build automated quality control and storage algorithms, complete spectral anomaly detection, spectral segment cutting, and batch naming, and record operation logs through triggers to ensure data version and operation traceability. Compared with traditional table based spectral data management methods, this spectral library exhibits higher stability in terms of data consistency and ease of use.

In terms of mapping methods, this study first used texture grouping as a clue to construct a sub model for texture spectral inversion, providing high-quality response variables for subsequent regional mapping. Subsequently, multiple covariates such as terrain, climate, vegetation index, land use, and parent material were selected, and textual data on soil formation environment and cultivation system in Hainan and surrounding areas were collected to fine tune the general large-scale model in different domains. The adaptive recommendation of partition covariates and model structure is completed by the large model, and the prediction is completed. Then, residual kriging is used to correct the error.

The results indicate that the Hainan Soil Spectral Database can significantly improve the robustness and portability of soil organic matter inversion. Compared with traditional mapping methods, the mapping method driven by large models achieves higher accuracy and more reasonable spatial distribution patterns in verifying sample points, especially in terrain transition areas and sparse sample areas where the advantages are more obvious. The final generated 30m resolution soil organic matter distribution map of Hainan Province can finely depict the differences between major agricultural land types, providing a new data foundation and methodological paradigm for farmland management in tropical regions.

# Effects of Soil pH on Spectral Inversion of Soil Organic Matter in Survey-Based Soil Spectral Libraries

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**ABSTRACT**

Survey-based soil spectral libraries provide a critical foundation for large-scale soil property estimation and agricultural management. However, their application is often constrained by variations in soil physicochemical conditions, among which soil pH represents a key but underexplored source of spectral heterogeneity. Soil pH regulates the chemical environment of soils and controls the ionization state, aggregation behavior, and mineral association of soil organic matter (SOM), thereby influencing soil aggregate structure and spectral absorption characteristics. In this study, we investigate how pH-driven changes in SOM states affect spectral responses and the stability of SOM prediction models within a laboratory-based spectral framework. Soil samples were collected from Hainan Province, China, a tropical region characterized by strong weathering, high Fe and Al oxide contents, and a wide pH gradient from strongly acidic to alkaline conditions. Laboratory Vis–NIR spectra and soil properties were analyzed by stratifying samples into four pH classes. Preliminary results indicate that strongly acidic soils exhibit weakened SOM-related absorption features, while neutral to weakly alkaline soils show more stable and distinct spectral responses. Comparisons among non-stratified models, pH-informed models, and pH-stratified models are conducted to evaluate the influence of pH on model robustness. This study highlights the importance of pH-aware strategies in the construction and application of survey-based soil spectral libraries and provides mechanistic insights for improving their reliability in agricultural management and soil monitoring.

**Keywords:** Soil organic matter; Soil pH; Soil spectroscopy; Spectral inversion; Survey-based soil spectral library

**Acknowledgments**

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# A Global Transformer Framework for Aligned Soil Spectral Analysis Across Sensors and Continents

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**ABSTRACT**

Soil spectroscopy is widely used for estimating soil properties, yet its large-scale application remains constrained by differences in sensor characteristics, spectral ranges, and resolutions. As global soil spectral collections increasingly combine data from heterogeneous instruments, there is a need for modeling frameworks that can align partially overlapping spectra without relying on sensor-specific calibration or strict wavelength standardization.

We propose a global transformer-based framework for aligned soil spectral analysis, coupled with an interoperable, web-based platform designed to support multi-sensor and multi-regional soil assessment. The framework is developed using a large and diverse soil spectral dataset comprising more than 80,000 samples, drawn primarily from open-access soil spectral databases, spanning five continents and covering visible–near infrared (VNIR) and mid-infrared (MIR) domains across multiple laboratory and field sensors.

At the methodological level, the framework adapts the Masked Autoencoder (MAE) paradigm to one-dimensional soil spectral signatures, using a self-supervised reconstruction objective to learn aligned representations from partially overlapping and incomplete spectral inputs. By reconstructing masked wavelength segments, the model accommodates variable wavelength coverage and sensor configurations without explicit spectral resampling or harmonization. Spatial context is integrated through latitude–longitude encodings based on sinusoidal positional features with learnable weights, enabling the joint modeling of spectral and geographic information.

Preliminary experiments indicate that representation-based modeling improves predictive performance relative to these baselines, with relative gains on the order of 10–20% in explained variance for key soil properties such as soil organic carbon and clay content, alongside consistent reductions in prediction error.

The learned representations and downstream predictions are made available through a global, publicly accessible web-based interface supporting multiple spectral formats and sensors. The platform is designed to provide consistent access to soil property estimates across regions lowering technical barriers for researchers, practitioners, and other stakeholders to interact with large-scale soil spectral data.

# Toward Global Soil Spectral Interoperability: Domain-Invariant Latent Embeddings with Federated Learning

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## ABSTRACT

Decentralizing soil spectral libraries is becoming essential for building globally robust soil-property models, because the most valuable datasets are spread across laboratories, universities, and agencies and cannot be readily pooled. In practice, cross-institution collaboration is frequently constrained by data sovereignty, intellectual property, and internal policy, making centralized "mega-libraries" difficult to establish even when the scientific value is clear. Meanwhile, libraries remain highly heterogeneous across regions and instruments, with differences in wavelength coverage, spectral resolution, sample preparation, and preprocessing protocols. This fragmentation induces strong domain shifts that degrade model transferability and motivates calibration-transfer and harmonization efforts that can operate in decentralized settings while preserving contributors' privacy. Federated learning (FL) offers a practical mechanism for multi-institution training without centralizing raw spectra, but standard averaging-based FL (e.g., FedAvg) can be insufficient under strong cross-client heterogeneity: client updates often drift toward local "lab/instrument style," resulting in weak generalization on mixed, held-out server test sets that better reflect real-world global deployment.

We propose a representation-first federated framework that learns a shared, library-invariant latent space and then performs downstream federated regression. In Stage 1, we pretrain a conditional variational autoencoder (cVAE) to map spectra into compact latent embeddings that preserve soil-relevant variation. To explicitly suppress library/instrument signatures, we attach a domain discriminator to the encoder and apply adversarial training with a gradient-reversal layer, encouraging embeddings that are informative for soil variation but uninformative of the originating library. In Stage 2, we train federated predictors on these embeddings to estimate key soil properties and indices.

In this setting, each partner retains a local, library-specific model and full control over its spectra and preprocessing choices while simultaneously contributing to a shared global model that would otherwise be infeasible or prohibitively time- and computationally demanding to build under centralized cross-country scenarios. Early results show that embedding-based federated training can achieve performance comparable to centralized pooling of libraries, while avoiding the exchange of raw measurements and sensitive metadata. By exchanging only model updates and compact, domain-invariant embeddings, the framework supports privacy- preserving global interoperability and provides a practical pathway for sustained, multi-partner collaboration without creating a centralized "mega-library."

# A Novel Soil Type Inference Method Using AI Large Language Models

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**ABSTRACT**

Based on pedogenetic theory, constructing soil-environment relationship models is a widely adopted approach for inferring soil types. While machine learning-based soil type inference models can characterize the complex nonlinear relationships between soil types and pedogenic environmental factors, they are unable to effectively integrate expert knowledge of soil genetic classification. In recent years, large language models (LLMs) represented by ChatGPT and Deepseek have developed rapidly, achieving a certain level of comprehension of pedological knowledge and thus providing a novel avenue for developing soil type prediction models that can incorporate expert knowledge of soil genetic classification. In this study, we collected soil sampling data and environmental data related to soil-forming factors. Guided by expert experience in soil genetic classification, numerical environmental variables were converted into textual knowledge, which was then encoded using LLMs to develop a soil type prediction model integrated with expert knowledge of soil genetic classification. To further enhance the overall predictive performance, ensemble learning methods were employed to fuse the inference results of machine learning-based numerical models and LLM-based knowledge models. Collectively, this study proposes a new perspective for the development of soil type inference models using AI LLMs, and may address the limitation that traditional inference methods cannot effectively integrate expert knowledge of soil genetic classification.

# The 3rd National Soil Survey of China: Integrating the Past and the Future

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**ABSTRACT**

National soil survey is often a great campaign in every part of the world. Up to now, only a few countries have announced conducting soil survey in national scale. Successful experiences from countries are different.

China conducted its second soil survey program in early 1980s, which coincided the great revolution of its land ownership system and massive adoption of new agricultural technologies. It is widely recognized that the second soil survey boosted the agricultural production and contributed enormously to food security.

After 40 years of dramatical changes of land use and management, substantial soil changes have been perceived via local and case studies. However, the whole picture of soil changes through the country is still a guess. Given this background, China launched its 3rd national soil survey in 2022. This five-year (including one year pilot survey) program aims to clearly illustrate the actual soil health conditions and how soils have changed after four decades of intensive soil use.

This new survey has fully taken advantage of modern soil survey technologies. Covering preselection of sampling sites, field operation tools, instant soil measurement and sophisticated data management technology, the survey have combined classical soil survey skills with cutting-edge GIS, RS and AI technologies, realizing a fast and more accurate data acquiring and processing for soil health assessment, soil suitability analysis and all-around interpretation. It is expected that this new survey will contribute to high-quality development in the coming decades and, provide a model to those areas may expect new soil survey or monitoring plans.

**Key words:** National Soil Survey, China, Big Data, AI

# Uncovering the spatial heterogeneity and drivers of grassland soil quality in Northwest China

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**ABSTRACT**

Grassland ecosystems in arid regions are highly vulnerable to degradation due to the synergistic effects of climate change and anthropogenic disturbance, yet comprehensive evaluations of grassland soil quality (GSQ) dynamics and controlling factors are still lacking. This study assessed the spatial variability and primary drivers of GSQ across four different types of grassland (lowland meadow, LM; temperate steppe, TS; temperate desert steppe, TDS; and temperate desert, TD) along an arid east-west transect in Northwest China, using an improved soil quality index method based on minimum (GSQImds) and total (GSQItds) datasets, to inform tailored management strategies. Results demonstrated strong correlations between GSQImds and GSQItds for all grassland types ($R^2$ values: LM = 0.93, TS = 0.74, TDS = 0.86, TD = 0.81; $P < 0.01$), with regression curves closely following the 1:1 line, confirming the reliability of minimum datasets for GSQ evaluation. LM and TS exhibited significantly higher GSQImds values (0.46 ± 0.13 and 0.45 ± 0.15, respectively) than TDS and TD (0.28 ± 0.14 and 0.31 ± 0.12, respectively) ($P < 0.05$). Spatially, GSQImds decreased with increasing aridity but displayed a bimodal relationship with altitude, peaking at low (<500 m) and high (>1500 m) elevations. Fencing significantly enhanced GSQ in TS and TDS but not in TD, indicating type-specific management responses. Random forest analysis identified soil properties as the dominant GSQ driver (42% contribution), followed by vegetation (21%), terrain (19%), grazing intensity (11%), and climate (7%). Structure equation modeling further revealed direct positive effects of soil and vegetation on GSQ, negative direct impacts from grazing, and indirect influences from terrain and climate. The generally low GSQ in the arid region of Northwest China underscores the urgent need for targeted soil management strategies, such as grazing exclusion, rotational grazing and revegetation, especially in arid and overgrazed areas.

**Acknowledgments**

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# Hydraulic Properties of Artificial Soil Constructed from Agricultural and Forestry Waste

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## ABSTRACT

The utilization of agricultural and forestry waste in creating artificial soils is a promising strategy for waste recycling and soil development. However, the impact of waste content on soil hydraulic properties remains a critical issue. This study aimed to investigate how replacing field soil with varying proportions (15%, 30%, 45%, and 60%) of mature agricultural and forestry waste (MAFR) affects the hydraulic properties of newly constructed artificial soils, thereby providing a theoretical basis for optimizing substrate formulations. We constructed layered artificial soils and compared four treatment groups (NL-1 to NL-4) against a control of pure field soil (HT). Key hydraulic parameters, including particle size distribution, saturated hydraulic conductivity (Ks), and soil water characteristic curves (SWCC), were systematically measured. Increasing the MAFR proportion generally enhanced soil structure, leading to higher saturated water content and Ks. Notably, the 45% replacement rate (NL-3) achieved the optimal balance, exhibiting the highest Ks (5.35 × 10-3 cm·s-1), which facilitates rapid drainage. While the 60% replacement (NL-4) improved porosity, its water retention curve indicated potentially weaker water holding capacity compared to other treatments. Interestingly, a critical threshold was observed at the 30% replacement rate, where the available water capacity (AWC) reached a minimum before increasing with higher MAFR additions, likely due to a shift in the soil's pore structure. The addition of MAFR significantly improves the hydraulic performance of artificial soils compared to pure field soil. The 45% replacement rate (NL-3) is recommended as the optimal formulation, achieving a superior balance between rapid water drainage and sufficient water availability, effectively addressing the poor aeration and slow water transport issues common in traditional field soils. These findings offer a practical guide for developing high-performance artificial soils from recycled organic waste.

# Investigating the Dry Color Requirement for Mollic and Umbric Horizons

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**ABSTRACT**

Soil color can act as a proxy for numerous soil properties including SOM, SOC, hydrologic regime, iron and manganese content, clay content, and minerology. In addition, soil classification often relies on color data, including the classification mollic and umbric horizons. However, there is little data available which provides scientific justification for the dry color requirements separating mollic and umbric epipedons. Consequently, the proposed work aims to address these knowledge gaps by investigating dark-soil color change upon drying. Moist and dry soil color data will be collected from the grasslands and eastern temperate forests of the United States using the Konica Minolta CR-410 Chroma Meter. Preliminary results show that forest soils increase in Munsell value (lightness) by 1.43 color chips upon drying, compared to 1.23 for grassland soils ($p<.001$). Forest soils had an average dry value of 4.26, compared to 3.86 for grassland soils ($p<.001$). While significant, these differences are not functionally useful for field classification purposes.

# The definitions of field characteristics in the WRB Field Guide

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**ABSTRACT**

Until the publication of its fourth edition (2022), the international soil classification system World References Base for Soil Resources (WRB) had a problem: The diagnostic criteria were using field soil science terms that were not defined in WRB. Neither were they defined in the FAO Guidelines for Soil Description (2006) that were often used to provide the field data for WRB classification. This became especially obvious during the field workshops of the IUSS Working Group WRB, when participants followed different understandings of field soil science terms. After some literature research, I found out where the terms were taken from: the Soil Survey Manual of the US Department of Agriculture, 1951. They were used in the Legend of the Soil Map of the World (FAO, 1974) and since 1998 in the WRB - without having been cited. Since that, they underwent some modifications - but still without definitions.

This changed with the Field Guide (Annex 1) of the fourth edition of WRB. In this talk, I will present some important (field) soil science terms, now defined for WRB (shorted definitions in this ABSTRACT):
- litter layer: loose layer with > 90% recognizable dead plant tissues (considered as a surface feature - not as a horizon)
- soil surface: directly below the litter layer
- mineral soil surface: upper limit of the uppermost layer consisting of mineral material
- soil layer and soil horizon
- soil and rock structure types (e.g. used in the criteria for the cambic, chernic, mollic, umbric, vertic and nitic horizon)
- concentrations (concretions, nodules, filaments, masses, coatings)
- redoximorphic features and their locations
- lithogenic variegates and initial weathering (to differentiate from redoximorphic features)
- stress features versus coatings
- cementation and cementation classes (needed for the criteria of the cemented horizons like petrocalcic etc., but also for cemented oximorphic features)

WRB often refers to percentages. Now, it is always stated what 100% is (by mass or by volume, fine earth, whole soil or fine earth in combination with specific soil constituents).

Precise definitions reduce complexity and avoid misunderstandings. Soil classification helps understand and use soil - but this requires unequivocal definitions.

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# Achievements and challenges for international classification of human-transformed and human-constructed soils

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**ABSTRACT**

Although soils altered by humans in terms of agricultural activities, aimed at increasing the productivity of originally infertile soils, were the first to be introduced into local and international soil classifications (as Anthrosols), today much more attention is paid to the soils of urban and industrial areas, which appeared in the FAO-WRB (World References Base for Soil Resources) classification as Technosols only in 2006. These two References Soil Groups (RSGs) are based on different concepts and different sets of diagnostic criteria, leading to different interpretations of the importance of particular human activities. A relatively small upbuilding of the topsoil layer by gradual or single addition of earthen fertilizers in order to improve soil productivity results in the recognition of the diagnostic terric or plaggic horizons, introduced to the soil name as respective principal qualifier. Whereas, deep upbuilding of the soil surface, deep soil remodelling, which destroys its natural morphological profile, or the construction of a completely new soil profile consisting of a local earthen material, situated on a new anthropogenic landform, may not be the basis for inclusion of these soils in any of the anthropogenic RSG and is marked with a lower grade supplementary qualifier, such as Relocatic, Transportic, and Escalic. New qualifiers naming variable kinds of artefacts or limiting layers in Technosols are added in subsequent editions of the WRB, while the landscape factor (landforms) seems to be underestimated in recognizing human-transformed sites and soils. In addition to the obvious development of the concept of Technosols, still many human-transformed and human-constructed soils appear to remain beyond Anthrosols and Technosols, including probably most of the soils of urbanized areas, vineyards and olive orchards, but also soils of archaeological sites. This opinion results in a fairly free interpretation of some diagnostic criteria and in a soil naming contrary to the rules of WRB classification, which is uncommon for the other ('natural') RSGs. After two decades since the introduction of Technosols to the WRB and the continuous development of this RSG, it seems necessary to comprehensively discuss and possibly revise the general concept of anthropogenic soils in the WRB, the criteria for separating between Anthrosols and Technosols, and the detailed criteria for diagnostic horizons and materials referring to human-transformed and human-constructed soils.

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# Reassessment of the anthropogenic soil's classification of Slovakia - basic principles and criteria

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**ABSTRACT**

Problem of adequate and correct description and classification of anthropogenic soils occurs very often and can result in very different approaches in many countries. To facilitate better development and refinement of classification criteria there is a need to differentiate newly defined human-transformed and human-constructed diagnostic horizons and properties. Also, confusing terminology of anthropogenic and urban soil terms and "anthropedosphere" is analysed. Ten soil classification systems over the world were overviewed in relation to applied principles and criteria of anthropogenic soils and substrates. Cultivated horizon is well-known described horizon in many scientific References, and no substantial changes are required. The real problem lies in technogenic soil types and their transient subtypes. Two groups of anthropogenic soils (cultivated and technogenic) are the subject of our reassessment in terms of soil classification principles, distinguishing criteria, and ordination into the soil References groups. The issue of re-evaluation of the current system of anthropogenic soils of the Morphogenetic Soil Classification (MSCS 2014) is observed in coincidence with anthropogenic Soil References Groups in the World References Base for Soil Resources (WRB 2022). Both observed groups are differentiated by cultivated horizon(s) (in the MSCS "in-situ" developed soil material) affected by permanent deep cultivation; and by anthropogenic horizon(s) (in the MSCS "ex-situ" developed from human transported and altered material (HTAM) as a result of technical human activities. The soil-forming substrate is a significant part of the soil mass especially for technogenic soils. Several improvements in technogenic soil diagnostics, including a new artefact percentage proposal have been proposed. Also list of anthropogenic substrata is highlighted as inevitable to consider. Some correlations with similar systems of anthropogenic soil and anthropogenic substrata were made and discussed. Recognition confirms a lack of anthropogenic substrates system in most soil classification systems. The connecting element is the References classification of WRB soils with related anthropogenic materials: artefacts, technic hard material and anthropic qualifiers. Comparing systems; several attributes were similar like presence of artifacts or human transported and altered material or human-induced properties like qualifiers Ekranic, Urbic, Spolic, or Garbic applied in Slovakia.

**Acknowledgment**

This work was supported by the Agency for Research and Development under contract No. APVV-15-0136 Impact of impermeable soil cover on urban climate in the context of climate change.

# Soils constructed and transformed by different cultures in the Mexico Basin: from the Teotihuacans to the Aztecs

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**ABSTRACT**

The earliest humans recorded in the Mexico Basin date back 30,000 years, although there is evidence that they inhabited small villages on the shores of Lake Texcoco during the Upper Pleistocene epoch, at the conclusion of the ice age. This period also saw a significant technological change, with more intensive and complex manufacturing of stone artifacts and obsidian tools. Despite the ample resources provided by the lake environment and the wooded areas, many native communities were marginalised to hilly areas or small islands in the ancient Lake Texcoco. This led to the construction of terraces and embankments for food production or building construction. The objective of the study was to characterize and classify the Anthrosols and Technosols built under different pre-Hispanic cultures in the Basin of Mexico. The geographical area under consideration is situated within the Neovolcanic Belt, in the central portion of contemporary Mexico. A comprehensive analysis was conducted on four distinct cultures: the Olmec, Teotihuacan, Aztec, and Acolhua. The main objective was the relationship between these cultures and soil construction and transformation. Subsequently, physical and chemical analyses were conducted, and the soils were classified according to the World References Base (WRB, 2022). The results of the study indicate that each culture had a different impact, depending on its needs and the environment, resulting in Technosols or Anthrosols. All pre-Hispanic cultures utilized obsidian in the fabrication of tools and weapons, the extraction of which commenced 2000 years ago. This activity resulted in a transformation of the environment, as substantial quantities of flakes and technical materials accumulated, leading to the formation of Technosols and, in some cases, Histosols-Technosols, as technical materials and organic materials (secondary vegetation) were intercalated. In the Teotihuacan area, the presence of Technosols, which contain technical materials such as volcanic tuffs or scoria, and different benches where crops were cultivated using cajetes (small holes) has been documented. The formation of Anthrosols occurred in Acolhua communities, where terraces were constructed for diverse purposes, including food production and the cultivation of medicinal and ornamental plants. An additional category of Anthrosols is represented by chinampas, a feature of Aztec culture, which are accumulations of lake sediments and organic materials, (constructed small island). This activity produced high-quality soil conducive to the cultivation of food, flowers, and vegetables, with two harvests per year. Given the diversity of activities and environments, soils can be classified very well at the References group level. Nevertheless, at the primary and secondary qualifier levels, the morphology and processes of these soils are not always reflected.

# History of the concept of Technosols, and other soils in urban areas

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**ABSTRACT**

The attempt to organize the research of soils in urban areas by the establishment of a Working Group Urban Soils (Arbeitskreis Stadtböden) of the German Soil Science Society by Wolfgang Burghardt in 1987 did confront soon soil scientists with the great amount of man-made, technic materials. 6 groups were distinguished: Ashes, slag, construction waste, rubbish, sewage sludge and industrial sludge, and others by the WG. Letters of Identification and Characteristics of Technic Substrates were developed for mapping, for knowledge about their functions and risk management. For designation G. Fried of the Federal Geological State Office of Bavaria made 1988 the proposal to distinguish 3 groups: Allosols - tipped natural soil material, Technosols - from technic material, and Phyrosols - from mixtures of both. The concept of Technosols was born. Blume reported from early soil mapping of the city of Berlin of clearly identifiable soil development processes (Ah-formation, browning, carbonate leaching etc.) in soils from technic materials similar as in natural soils. He showed by this that soils from technic substrates can be included in the system of classification of natural soils. Thus Technoregosols, Calcaric Technoregosols etc. were created and are content of German urban soil maps, e.g. of the city of Berlin.

The ISSS established a WG Urban Soils on the 16th WCSS in Montpellier, France, 1998. The first conference was organized in Essen, Germany by Wolfgang Burghardt and titled SUITMA-Soils of Urban, Industrial, Traffic and Mining Areas. Thus SUITMAs became the name for urban soils. By international interest urban soils became a thematic of WRB. Andreas Lehmann proposed the inclusion of Technosols in the WRB 2006. By Peter Schad and Andreas Lehman an excursion about urban soils in the heavy industry region of the Ruhr, and the cities Halle and Stuttgart, Germany was organized. The soil group Technosols with detailed description of Qualifiers was included in the WRB (2014). Technosols are defined in the WRB (2006,2014) as soils without significant or only weak soil development processes. However, urban soil investigations cited already a number of different distinct visible processes in some Technosols. There are two types: 1. Changes of the deposited technic substrates and 2. by processes induced by the urban environment. Example for 1. are slags from iron industry which are from Ca-silicates and are transformed to CaCO3. This formation to Carbonatosols happens within few decades. Concrete consist of Ca-Silicate too. It occurs frequent in urban soils. Studies are missing, 2. Dust infiltrates in gaps of pavement stones and plates (Dialeimmasols), particle intrusion occurs in diverse types of macadam (Particle Intrusols), reduction conditions by oxygen deficit underneath sealed sites (Reductosols). Beside them large areas are occupied by relict, cut, fossil, micro- and meso-climate controlled, and intense drained or leached soils.

# Extending Technosols? The status of human-transported materials in soil classification

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**ABSTRACT**

Technosols are commonly recognized as the most explicitly anthropogenic soil group. However, their definition in the World References Base for Soil Resources (WRB) remains largely dependent on the presence of diagnostic technical features—particularly man-made artefacts, technogenic hard material or geomembranes. As a consequence, WRB limits Technosols to soils that contain artificial products, excluding many soils derived from human activity that involves s boil material redeposition but not fabrication.

This raises a key question for modern soil cartography: should human-transported mineral material be incorporated into the definition of Technosols, even when it does not contain artefacts? In numerous engineered landforms—road embankments, reconstructed riverbanks, mining spoil, urban terraces, and flood protection structures—humans act as the dominant geomorphic agent. The substrate is therefore anthropogenic not because it contains industrial residues, but because it was redeposited purposefully by humans. Under current WRB rules, such soils – if they do not contain well-developed humus horizons, are commonly classified as other References Soil Groups (as weakly developed Regosols), despite their clearly technogenic origin and associated land-use implications.

Some national systems already acknowledge this issue. For example, the Polish Soil Classification (6th edition, 2019) includes Aggerosols, formed from thick layers of human-redeposited mineral material that later undergo natural pedogenesis, even if artefacts are absent. This approach treats human redeposition as a soil-forming process and views anthropogenic parent material itself as a valid diagnostic factor.

This presentation examines whether human-transported substrates should be recognized as technogenic diagnostic material, thus expanding the Technosol definition. Using parallel classification of selected soil profiles, we explore the conceptual consequences of such an extension for WRB, its impact on mapping and land evaluation, and the broader question of how soil classification systems should represent human agency: through artefacts, through parent material, or through both.

# Proposals for Urbic Technosols in World References Base

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**ABSTRACT**

New data on urban soils accumulated in this century, display their specific properties along with their high diversity owing to their occurrence all over the world. Urban soils deserve a more prominent position in WRB system and some "urbipedological" qualifiers for soils beyond the Technosols RSG. The first step might be a transfer of Urbic qualifier to urbic diagnostic horizon, as it is in the Russian system; the second – enlarging the definition, the third – introducing additional urbic qualifiers.

1. Arguments in favor of urbic horizon: emphasizing the specific nature of soils in city environment and increasing urban soils importance in the array of native soils, providing a pedogenetic ingredient in urban soils. Our perception of urban soils comprises continuous accumulation of solid-phase material different in texture and/or composition (strata), both casual and intentional, and its reworking with time in a soil with urbic horizon. Therefore, such soil is named urbistratozem – a central image of urban soils; in old cities it merges with the cultural layer. Urbic Technosols with urbic horizon may have Supplementary qualifiers Urbinovic for younger soils and Urbistratic for older ones with a discriminating boundary of 20cm.

2.The definition of Urbic qualifier (WRB,2022) comprises depth-thickness parameters, share of peculiar artefacts, human-produced waste in settlements. These criteria are applicable to any material (HAM and HTM of J. Howard), and lack pedogenetic features, inevitable in a live environment on the earth surface. Such soil properties as Corg content, pedogenic structure, infiltration rate, CEC, elevated pH values, participation of biota, etc. are recommended as criteria for urbic horizon, they are accepted in the Russian soil classification system.

3. The effect of urban environment on soils and sediments varies in intensity depending on the time elapsed, human activities, initial material, and along with urbistratozems, there are soils in settlements with a "weak" urbic horizon, hence, urbic property overlying the initial soil or technogenic material. In the former case, Urbinovic Supplementary qualifier may be added to the soil name, in the latter case – Urbithyric qualifier may be proposed as Supplementary to Regosol or Arenosol. For purposefully constructed soils, we propose Artiurbic qualifier as a Principal one for Technosols, since such soils are composed of HTM arranged in a non-natural sequence adapted to urban requirements.

We also have doubts about most of supplementary agricultural qualifiers in the Technosols RG. It seems hardly possible to find rice pads or plaggen land use system (with pigs and heatherlands) in a city or abandoned mines.

# Characterization and Classification of Soils on Sedimentary Parent Rock in Kobape, Southwestern Nigeria

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**ABSTRACT**

This study investigates the characterization and classification of soils derived from sedimentary parent rock in Kobape, Southwestern Nigeria, to enhance the understanding of soil properties and their implications for land use management. The research was conducted in the sedimentary terrain of the Dahomey Basin, covering an area of 8.203 hectares, where three soil units A, B, and C were identified for soil sampling. Morphological, physical, chemical, and biological properties were assessed, with soil depth ranging from 121 to 130 cm, indicating deep soils. The pH values ranged from 4.68 to 5.57, signifying strong to moderate acidity, while electrical conductivity (EC) values varied from 0.01 to 0.58 dS/m, indicating low salinity. Base saturation was measured between 28.33% and 65.02%, revealing low to moderate fertility levels. Total iron content showed high concentrations ranging from 66.60 to 333.90 mg/kg, indicative of intense weathering typical of tropical soils. The study identified dominant sandy textures, with bulk density values ranging from 1.41 to 1.55 g/cm³, indicating moderate compaction. The soils were classified according to the USDA Soil Taxonomy as follows: soil unit A as Ultic Paleustalfs, soil unit B as Ultic Haplustalfs, and soil unit C as Typic Dystrustepts. The classification according to FAO/UNESCO identified units A and B as Haplic Clayic Lixisols, while unit C was categorized as Dystric Clayic Regosols. Given the pressures on agricultural land and the rising demand for food production, this research emphasizes the need for comprehensive soil assessments to inform sustainable agricultural practices. The findings contribute valuable insights to food security and environmental sustainability efforts in the region, advocating for the integration of soil management practices tailored to the classified soil types.

**Keywords:** Land use, Soil, Properties, Characterization, Classification

# The classification Salt-affected Soil in Reclaimed Agricultural Tide

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**ABSTRACT**

Globally, the classification of saline soils is mostly based on soils in arid and semi-arid regions. The WRB, one of the globally accepted soil classification systems, classifies saline soils as Solonchaks, which means soils with a high concentration of soluble salts. The conditions that must be met for a soil to be classified as Solonchaks are: first, the salic layer must begin within 50 cm of the soil surface, Second, the thionic stratum must not begin within 50 cm of the soil surface, and finally it must not be permanently submerged and not located below the tidal influence line. The salic stratum is characterized by a saturated extraction pH greater than or equal to 8.5, measured at 25 °C per year, and a saturated extraction electrical conductivity(ECe) greater than or equal to 8 dS m-1, the product of the electrical conductivity(ECe) value and the stratigraphic thickness is greater than or equal to 240, or the saturated extractive electrical conductivity(ECe) measured at 25 °C is greater than or equal to 15 dS m-1 and the product of the electrical conductivity(ECe) value and the stratigraphic thickness is greater than or equal to 450. In the U.S., the Salinity Laboratory's criteria categorizes them as saline, alkali, and saline-alkali. The analytes required for classification are electrical conductivity(ECe), pH, sodium adsorption ratio(SAR), and exchangeable sodium percentage (ESP), and they are classified according to the criteria presented in Table 1. However, saline soils in Korea are soils formed by reclamation activities rather than arid and semi-arid regions, and there is a lack of research on setting salinity criteria. Therefore, this study was conducted to classify reclaimed saline soils distributed in Korea according to the criteria of WRB and the U.S. Saltwater Research Institute, to present the problems of reclaimed soil classification, and to set appropriate criteria for Korea

**Acknowledgments**

Table 1. US Salinity Laboratory Staff Classification

| Classification | Electrical Conductivity (mmohs/cm) | Soil pH | Exchangeable soudium % | Soil Condition | Physical |
|---|---|---|---|---|---|
| Saline soil | >4.0 | <8.5 | <15 | Normal | |
| Sodic soil | <4.0 | >8.5 | >15 | Poor | |
| Saline-Sodic soil | >4.0 | <8.5 | >15 | Normal | |
| | >=greater than, <=less than | | | | |

# Identifying Lithic Discontinuities in Volcanic Soils Using Particle-Size Analysis: A Comparative Study of Andosols and Nitisols Along a Toposequence in Western Java, Indonesia

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**ABSTRACT**

Safeguarding the future of humanity requires caring for the health of our soils. Soil classification relies on insights into soil formation and functioning, based on the premise that this provides tools for sustainable soil management. Identifying diagnostic features, which are key to modern soil classification, is often far from straightforward. This study investigates lithic discontinuities in volcanic soils along a toposequence comprising three Andosols and three Nitisols. In Western Java, Andosols dominate at higher elevations, while Nitisols occur in mid-slope positions. Andosols form through rapid weathering of volcanic ash in the presence of organic matter, producing horizons rich in allophane, Al–humus complexes, or volcanic glass, and typically exhibit heterogeneous profiles reflecting multiple eruptions. In contrast, Nitisols represent an intermediate weathering stage involving ferralitization, with silica and base leaching leaving kaolinite and sesquioxides, combined with nitidization and intensive bioturbation that generates a well-structured topsoil.

In the WRB-2022 (IUSS Working Group WRB, 2022), identifying lithic discontinuities is crucial for evaluating whether diagnostic horizons are pedogenic. These discontinuities represent significant breaks between parent materials, often marking separate depositional events, and may occur between strata of similar or different mineralogy. Determining whether two layers are separated by such a break requires checking numerous alternative criteria, several with nested subcriteria, making their application difficult and leading to ambiguous classification and genesis interpretations.

Using hierarchical cluster analysis, we apply a modified version of the method introduced by Langohr et al. (1976), which uses particle-size distribution to identify lithic discontinuities. Our findings reveal far more frequent and clearer lithological breaks in the Andosols than in the Nitisols, despite both soils having developed from similar volcanic parent materials. This contrast is attributed to differences in age and climatic influences, with Nitisols exhibiting greater homogeneity. Morphological, chemical, and mineralogical data corroborate the identified discontinuities and support the robustness of the adapted method. Our approach offers a practical alternative to the complex WRB criteria and improves understanding of soil formation processes in tropical volcanic landscapes.

**Key words:** soil formation, Hierarchical Cluster Analysis, Andosols, Nitisols

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# Towards Better Classification of Human-Altered Soils In WRB: a Systematic Framework and New Qualifiers

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**ABSTRACT**

Worldwide, human pressure on soils has intensified due to the combined effects of agricultural expansion, urbanization—both in cities and rural settlements—and increasingly dense infrastructural networks. A key driver of this trend is rapid population growth, particularly in the Global South.

We present a comprehensive framework that systematically covers the various types of human interventions affecting soil formation, soil properties, and soil functioning, including the addition of soil material and artefacts to in-situ soils, the reshaping of soil, the removal of soil, and the use of soil material for construction purposes. Particular attention is given to human-induced alterations of diagnostic horizons.

Based on the classification of about 1,600 References soil profiles, we conclude that a wide range of direct and indirect human interventions in soils are not fully captured by the current WRB nomenclature. Drawing on our framework, we propose several new supplementary qualifiers to better characterize human-altered soils. Their applicability must be further tested and documented. However, because non-agricultural human-altered soils are under-represented in conventional soil survey databases, additional efforts will be required to incorporate data from soils described, for example, at archaeological excavation sites.

**Key words**: WRB, Anthrosols, Technosols, Anthric, Anthropedogenesis

# Research on the classification of human-altered soils in China

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**ABSTRACT**

With accelerating urbanization and the global call for "Healthy Soils, Healthy Cities," the scientific classification and management of human-altered and human-transported soils have become essential for sustainable urban development. International systems such as the US Soil Taxonomy and the World References Base for soil resources provide diagnostic criteria for anthropogenic influences. As one of the countries with the longest history and most intensive degree of human activity, China possesses unique advantages but also faces severe challenges in the classification of its human-altered soils. This study reviews the historical development of human-altered soil classification in China and highlights the progress made in the Third National Soil Survey, where a new suborder for human-engineered soils was introduced to address soils derived from engineering activities. To evaluate the practical applicability of the new classification scheme, this study selected 15 representative soil profiles with engineering technical characteristics from Beijing, Hebei, Henan, and Guangdong for empirical assessment. The evaluation shows that although 80% of the profiles can be properly classified into the newly added categories, key limitations remain, including inadequate categorization of polluted soils, insufficient characterization of sealed soils, and the classification of engineering fill materials was not refined enough. To address these gaps, this study propose a refined classification scheme for China's human-altered soils. It is proposed to add the Technic hardpan as an important diagnostic horizon for identifying human-altered soils. The Technic hardpan should include: Fill materials Layers, Barrier layer, and Contaminated layer. Within the Anthrosols order to accommodate soils with distinct engineering technical characteristics, a Technic Anthrosols suborder is established, comprising Transporti-Technic Anthrosols and Alteri-Technic Anthrosols groups with Contaminated, Barrier, Intrusive, and Typic subgroups. And it is recommended to add Technical Soil Family category, including Toxic, Sealed, Slow permeable, Reconstructed, Rubbish. The proposed framework enhances the scientific rigor and applicability of human-altered soil classification in China, supports urban soil health assessment and sustainable utilization, and provides a Chinese contribution to global efforts in managing anthropogenic soils.

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# The rationale behind the revision of the German Soil Systematics

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**ABSTRACT**

The roots and architecture of the current German Soil Systematics go back to the 1950ies. Taking up the ideas of Kubiena's "Soils of Europe" (Kubiena 1953), a natural system of soils was formulated that covered the pedogenetic processes which are or were active in Central Europe. The major advantages of the system's architecture were that (i) it has clear guiding soil-scientific principles, (ii) well-thought categories even on its highest hierarchical level (called divisions) covering the different water regimes, (iii) allows to incorporate not only natural, but also anthropogenic processes of soil formation, (iv) its flexibility in definig transitional soil types, and (v) last but not least its usefulness in soil survey and mapping.

After altogether eight revisions, we again and fundamentally revised the system for the new sixth edition of the German Soil Survey Guidelines that was published in 2024. First of all, soils not yet covered in the system should be included: soils (i) with advanced peat degradation with characteristics that not existed earlier, (ii) with lateral accumulation by interflow water, (iii) completely remodelled by man, and (iv) not least the Andosols and Umbrisols of WRB, which had no correlatives in the system so far. A second task was to make the system more systematic itself by removing grown inconsistencies had become part of the system, e.g. that soil characteristics resulting from similar soil forming processes were considered on different hierarchical levels in the groundwater and stagnant water affected soils classes. The marshland soils that developped by land reclamation activities along the tidal coasts of the North Sea, had a mere geographic definition rather than a definition based on a soil forming process.

The higher hierarchy of the system (division – class) had to be revised completely, to incorporate a soil-forming processes from the landscape level into a system that considered matter translocation only in vertical direction only. The former water regime-oriented definition of divisions has been extended to (now sub-)divisions of water and oxygen availability regimes. The new division level (mineral and organic soils) facilitates to identify soils with a high significance in the climate system. New classes (Andosols, Rheosols) were defined, while the epi-tidal marsh soils class has been split up and types shifted to the classes Gleye and Stagnant water soils.

As a result, the current system kept the advantages of the old system, but gained rigor and apliccability for present scientific and soil survey-related tasks. Sticking to the scientific idea behind the system – to reflect soil formation paths – instead of sticking to a tradition of formerly formulated units of the system, maintains the system's function: to have scientifically meaningful units that respond in a similar way to (environmental) processes and changes and that can, without further intermediate steps, be used in soil survey.

# Soil characterization as a tool for sustainable soil management in the Assam-Meghalaya foothill belt: Implications for humanity's shared future

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**ABSTRACT**

Soil classification provides a critical framework for understanding soil behavior and guiding sustainable land use decisions essential for humanity's shared future. In densely populated and environmentally fragile regions, such as the Assam-Meghalaya foothill belt of India, fine-scale soil information is indispensable for balancing food production, ecosystem resilience, and livelihood security. This study presents a detailed pedological characterization and large-scale (1:10,000) soil classification of the Rangjuli block, Goalpara district, located at the interface of the lower Brahmaputra alluvial plain and the Meghalaya plateau.

A total of 76 soil profiles across 41 landscape ecological units were examined using field morphological descriptions, laboratory analyses of physical and chemical properties, and USDA Soil Taxonomy. Eight soil series: Ambari, Kamarpota, Kahibari, Simlitola, Madong, Sildubi, Athiabari, and Ambuk, were identified, representing Inceptisols, Alfisols, and Ultisols. Soils ranged from deep to very deep (100 to >150 cm), with textures from loam to clay, drainage classes from poorly drained floodplains to well-drained uplands, and acidic reaction (pH 4.52-5.96). Variations in organic carbon (0.53-1.98%), base saturation (18.6-94.5%), and cation exchange capacity (6.1-12.8 cmol(p+) kg-1) reflected differences in topography, parent material, drainage, and degree of weathering.

Soil classification revealed a continuum from young, hydromorphic alluvial soils suited to paddy-based systems to mature, leached upland soils better suited for plantations, agroforestry, and perennial land uses. By translating soil diversity into functional land use guidance, this study demonstrates how soil classification underpins site-specific management, reduces land degradation risks, and supports sustainable agricultural intensification-key components of a resilient and equitable future for humanity.

**Keywords:** Soil heterogeneity, Toposequence, Land use, Assam-Meghalaya foothills, Soil characterization

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# Soil classification as a carrier of functional information in viticultural terroir: linking pedogenesis and wine metabolomics

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**ABSTRACT**

Soil classification systems, such as the World References Base for soil resources (WRB) and Soil Taxonomy, are traditionally used for soil survey, land evaluation, and data harmonisation. However, their potential to encode functionally meaningful information relevant to complex agro-ecosystems remains underexploited. In viticulture, soil is a key component of terroir, yet its influence is often assessed through site-specific physicochemical measurements rather than through integrative classificatory frameworks. This study explores whether formal soil classification systems can act as carriers of functional information capable of explaining grapevine metabolic responses and wine composition.

Eight vineyard soils from a Mediterranean wine district in southwestern Sicily were selected to represent contrasting pedogenetic pathways under controlled agronomic conditions. Each soil was morphologically described, analytically characterised, and classified according to both the WRB and Soil Taxonomy. Wines produced from grapes harvested in the immediate vicinity of each soil profile were subjected to targeted metabolomic analysis, focusing on phenolic and volatile compounds. Multivariate statistical approaches, including Principal Component Analysis and Partial Least Squares Regression, were applied to investigate relationships between soil classification descriptors and wine metabolomic profiles.

Results indicate that specific taxonomic elements, particularly those related to horizon development, texture, and secondary carbonate accumulation, explain a significant portion of metabolomic variability. After accounting for varietal effects, soils classified as Luvisols/Alfisols showed relatively homogeneous metabolic signatures, while Calcisols/Calcixerepts exhibited greater dispersion, reflecting contrasting hydrological and chemical constraints. Both classification systems captured pedogenetic attributes that align with known soil–plant interaction mechanisms, although WRB qualifiers related to horizon architecture provided a slightly more coherent latent structure in multivariate models.

These findings support the view that soil classification systems are not merely descriptive tools, but integrative frameworks that synthesise pedogenetic history into functionally relevant information. By linking taxonomic descriptors to independent biological outputs such as wine metabolomics, this work contributes to repositioning soil classification within process-based interpretations of terroir. More broadly, it highlights the potential of classification systems to support transferable, function-oriented approaches in agroecosystem assessment, bridging traditional pedology with emerging modelling and decision-support frameworks.

# Appraisal of Soil Taxonomy and the World References Base for Soil Resources Applied to Classify Purple Soils from the Eastern Sichuan Basin, China

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**ABSTRACT**

Purple soil is a type of global soil that is referred to by various names in different countries,which makes it difficult to understand, utilize, and ameliorate purple soil internationally.Soil Taxonomy (ST) and the World References Base for Soil Resources (WRB) are the most widely used soil classification systems in the world.The aim of this study was to clarify the classification of purple soil in ST and the WRB and to establish a References between different classification systems of purple soil.Therefore, based on the current principles and methods of the ST and WRB systems, 18 typical purple soil profiles in the eastern Sichuan Basin were identified, retrieved, and classified.Then, the soil units of the WRB were compared with those of ST and the Chinese Soil Taxonomy (CST).The results revealed that the 18 typical purple soil profiles could be classified into three soil orders, four soil group orders, and seven soil subgroups in ST and four References soil groups (RSGs) in the WRB;each profile had its own unique principal and supplementary qualifier combinations within the soil units.It was found that when compared with the ST system, the WRB and CST systems had stronger abilities to distinguish purple soil.In addition, the WRB system was able to more comprehensively consider soil characteristics such as soil layer thickness, ferric horizon, soil color, texture mutations,and carbonate through qualifiers.However, the CST system added diagnostic characteristics, such as the lithologic characteristics of purplish sandstones and shales and the ferric properties and alic properties at the soil group and subgroup levels, which enhanced the differentiation ability of the purple soil at the subgroup level.

# Towards a simplified key and groupings of the World Resource Base for Soil Resources (WRB)

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**ABSTRACT**

The WRB classification system has become more of a method to describe and classify any soil encountered in the world rather that to characterize and name a spatial pattern on soil maps, while it should serve both purposes. We propose to change the governance of WRB for future deciding on changes to the system, work towards a simplified system to be used in parallel, and to better facilitate FAIR data storage of WRB in databases.

New criteria and diagnostics in the subsequent soil classification have been based mainly on field trips of the working group that looked at a limited set of soil profiles. This has led to a focus on soil profile classification rather than the mappable soil unit classification. In an effort to summarize all features of the soil profile, the qualifiers and sub-qualifiers proliferated. With this complexity, the chance of adoption by students and researchers becomes less. For database management and for standardizing and harmonizing data, the current WRB classifications are not easily accommodated because of the many qualifier combinations possible (certainly with the depth indicators added) and the change of concepts and protocols over time.

A standard protocol for the paragraph 2.3 in the WRB manual (Rules for creating map legends) has not been worked out. Nachtergaele et al. (2022), in a draft proposal to the WRB working group, proposed a simplified system for mapping WRB units. It includes to define Soil Units by a maximum 2 PQ's. For classification, soil units are further characterized by SQ's with the textural class SQ always first, followed by Skeletic - if applicable - and then all other SQ's in alphabetical order. Another simplification could be to group RSGs with similar formative processes and soil functions into broader groups (Soil Units above References Soil Groups), such as soils with high organic matter content (Chernozems-Kastanozems-Phaeozems, Umbrisols), arid soils (Solonchaks, Solonetz, Gypsisols, Calcisol, Durisols)and so forth. Evidently the grouping can and will be much debated.

A simplified system with ranked PQs will also facilitate a better backward compatibility with earlier version of the system and would also facilitate the inclusion of WRB classification for FAIR data storage of WRB in database. We propose that subgroups within WRB work on an online documentation of the WRB codelists and vocabularies (standardized, controlled lists of terms and codes used to ensure consistent data description and exchange) and a simplified system for mapping WRB units. A more user-friendly documentation would need to be developed in parallel.

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# Soils of stone-wall bench terraced anthroscapes: A proposal for their classification

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**ABSTRACT**

Stone-wall bench terraces are widespread in Mediterranean regions, extending across both slopes and valley bottoms, creating distinct anthroscapes where hydrology, soil erosion, and development are largely shaped by the terraces themselves. Most of these terraces were (re)constructed at the end of the 19th century in the eastern Iberian Peninsula, and while they remain stable when properly maintained, land degradation occurs upon abandonement. It is essential to recognize the singularity of these man made soilscapes in order to classify and map soils accurately, contributing to the preservation of these valuable and diverse soil resources, especially amid increasing water scarcity in Mediterranean areas. In these anthropogenic landscapes, the concept of "human-transported material" is applicable. Based on this, and considering soil development along with parameters such as terrace size (height and length) and intensity (meters of stone-wall bench terraces per hectare) we propose a classification for these soils as Anthrosols (IUSS Working Group WRB, 2022), aiming to make them more relevant in soil mapping and land use planning.

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# Differences in chemical properties and soil classification of Andosols under varying volcanic ash deposition in the caldera rim of Mt. Aso, Kyusyu Islands, Japan

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**ABSTRACT**

Mt. Aso, located in Kyushu, Japan, is one of the world's largest active volcanoes. The soil in the caldera rim is Andosols. Naka-dake, the only active volcano in the central crater hills, continuously emits sandy volcanic ash that is transported eastward by the westerlies, producing thick ash deposits in the eastern rim (Miyabuchi et al., 2003). Consequently, soil formation in the eastern rim is considered younger than in other regions. In comparison, Yamaguchi et al. (2017) reported the properties of Andosols in the northern caldera rim, an area less influenced by fresh volcanic ash, and found that they have high carbon contents. However, the relationship between volcanic ash deposition and the formation process of Andosols in the Aso region has not yet been sufficiently documented.

Therefore, this study conducted soil surveys on grasslands in the eastern caldera rim and classified the soils using the Japanese Soil Classification System (Japanese Society of Pedology, 2017), WRB (IUSS, 2022), and Soil Taxonomy (USDA, 2022). This revealed the characteristics of Andosols formed under fresh volcanic ash accumulation and the properties reflected in each soil classification.

The results showed that Andosols in the eastern rim had lower soil carbon concentration, a loamy soil texture, and tended to have higher base saturation than the northern rim (Yamaguchi et al.,2017). According to the Japanese Soil Classification System, both sites were classified as "Cumulic Allophanic Andosols." In the WRB, Site 1 in the north was classified was "Hydric Silandic Andosols (Acroxic, Hyperhumic)," Site 2 was "Hypereutric Hydric Silandic Andosols (Hyperhumic)," and the eastern site was "Oligoeutric Silandic Andosols (Loamic, Profundhumic)," reflecting differences in base saturation, water-holding capacity, and soil carbon concentration. In Soil Taxonomy, Site 1 was "Acrudoxic Hydric Melanudands," Site 2 was "Hydric Pachic Melanudands," and the eastern site was "Typic Hapludands," reflecting differences in organic matter quality and resulting in different Great Group classification. Thus, even within the Aso caldera rim, the characteristics of the Andosols differ due to volcanic ash deposition. While both the WRB and Soil Taxonomy capture these differences, the properties they reflect differ. It is considered necessary to use them appropriately depending on the classification objective.

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# AI Multiagent Systems as Partners in Discovery and Knowledge Synthesis for Soil Science Research

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**ABSTRACT**

Soil science is entering a new phase with the emergence of artificial intelligence (AI) multiagent systems. Here, we explore the potential of AI multiagent systems as a framework to support hypothesis generation, experimental design, and conceptual synthesis in soil science.

We illustrate this approach using the case of soil carbon saturation, focusing particularly on mineral-associated organic carbon (MAOC). The saturation concept posits that mineral surfaces provide finite reactive surfaces for stabilizing organic matter, implying an upper bound to long-term carbon storage. However, recent empirical evidence shows contrasting patterns: some studies report near-linear increases in MAOC even under high carbon inputs, while others emphasize methodological artefacts and the need to distinguish practical (effective) saturation from theoretical mineral capacity. This ongoing debate makes carbon saturation an ideal test case for structured hypothesis generation assisted by AI. We tasked a general-purpose multiagent AI system, to generate scientific hypotheses and experimental designs addressing key uncertainties surrounding MAOC saturation. The AI agent operates through three collaborative agents—Planner, Executor, and Verifier—that collectively search literature, synthesize knowledge, generate hypotheses, simulate critique, and evaluate alternative perspectives. The resulting hypothesis set encompassed five thematic areas: (1) effective versus theoretical saturation thresholds; (2) microbial and molecular controls on MAOC formation; (3) climate-sensitive vulnerability and persistence of MAOC; (4) cross-disciplinary mechanisms such as adsorption, aggregation, and co-precipitation; and (5) management strategies aligned to saturation state. The simulated peer review process judged the hypotheses to be conceptually coherent, diverse, and largely aligned with contemporary soil carbon frameworks.

We argue that AI multiagent systems, guided by domain experts, can accelerate early-stage discovery, support interdisciplinary integration, and formalize the often tacit reasoning involved in scientific framing. However, this should be understood as augmentative, not substitutive: challenges remain in ensuring data quality, maintaining transparency and interpretability, preventing epistemic over-trust, and safeguarding the foundational role of human scientific judgment. Multiagent AI systems have the potential to become powerful partners in designing and testing soil science knowledge, particularly as we confront global challenges requiring rapid yet rigorous scientific innovation.

# Climate and Land Use Independent Modelling of Soil Carbon Stocks

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**ABSTRACT**

As the largest store of terrestrial organic carbon, soils play a critical role in maintaining the essential ecosystem services needed to sustain life on Earth. However, accurate estimates of global and regional carbon stocks at depth, where most of the sequestered soil carbon is stored, are difficult to determine because of soil heterogeneity and variation in the physicochemical environment over relatively short scales. As such, many modeling approaches rely on measured soil properties to estimate carbon stocks down the profile. Such parameters are not easily measured at depth and a new approach, one that can be universally applied across all soils systems, is required. Here, we present a simple, unified, mathematical model for estimating subsoil carbon using huge routinely measured topsoil (0-20 cm depth) data and two key developed parameters. Model validation was done using 22,579 soil profiles representing 11 climate zones, and 7 land use types across 149 countries and shown to be accurate and highly significant. We estimated that the global SOC stocks at 1746 and 2177 Pg in 0-1 m and 0-2 m depth, respectively. It also suggested that current models may be underestimating total soil carbon at depths to 2 metres. Our model provides robust and universal method for boosting the accuracy of global SOC projections.

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# Pedological controls reshape global projections of soil respiration and soil carbon–climate feedbacks under climate change scenarios

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## ABSTRACT

Soil respiration constitutes one of the largest carbon fluxes from land to the atmosphere and can reinforce or attenuate climate change throughout the 21st century. Nevertheless, global projections of total soil respiration (Rs) and heterotrophic respiration (Rh) still show high uncertainty, partly because global scale models tend to prioritize climate and vegetation covariates, with limited representation of pedological modulators, and because validation strategies that allow spatial and temporal leakage may overestimate generalization capacity. In this study, we evaluated the influence of soil texture on future global projections of Rs and Rh up to 2100 under SSP1-2.6, SSP3-7.0, and SSP5-8.5, quantifying the effect of including versus excluding textural variables on the estimates and associated uncertainty. We compiled annual field measurements from SRDB V5 for Rs (n = 3,288) and Rh (n = 832) and fitted machine learning models (Quantile Random Forest) to estimate fluxes and uncertainty using climatic predictors (CHELSA v2.1), net primary productivity, and pedological covariates, including soil texture and soil organic carbon from SoilGrids 2.0 and clay mineral maps. We applied repeated spatially conditioned cross validation so that observations with identical coordinates remained in the same fold, preventing artificially high performance due to temporal replicates at the same site. This strategy reduced apparent overfitting, lowering mean test $R^2$ from about 0.65 to 0.28 for Rs and from about 0.61 to 0.18 for Rh. The final model estimated present day global fluxes of 91.9 Pg C $yr^{-1}$ for Rs and 58.0 Pg C $yr^{-1}$ for Rh. For 2071–2100, projections under SSP1-2.6, SSP3-7.0, and SSP5-8.5, combined with five CMIP6 models, indicated stronger increases in Rs and Rh at high northern latitudes and smaller changes, or slight declines, in humid tropics. In the tundra, Rh increased more than Rs, which raised the Rh to Rs ratio and indicated a greater propensity for a positive soil carbon–climate feedback where warming is strongest. The inclusion of texture variables, especially clay content and the ratio of soil organic carbon to sand as a proxy for vulnerability to mineralization, reduced projected Rh and decreased inter model spread compared with configurations that excluded texture and relied primarily on climate. These results support that, even under generalized temperature increases across scenarios, soil texture and the associated mineral protection impose pedological controls that modulate the sensitivity of Rs and Rh to warming, indicating that temperature driven projections may overestimate fluxes and the magnitude of the soil carbon–climate feedback in certain environments. Projected uncertainty remained high in regions with low observation density, reinforcing the need to expand Rs and Rh measurements, especially at high latitudes.

# Use of Geophysical Methods for Mapping Eucalyptus Root Systems in Different Soil Types

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**ABSTRACT**

The study of root systems is essential for understanding key ecological and physiological processes in plants, such as water and nutrient uptake, soil stabilization, and interactions with microorganisms. However, root system investigations are challenging and costly due to limited access to the subsurface. Traditional approaches are predominantly destructive, including excavation and analyses of seedlings grown in pots or observation systems such as rhizotrons, which, despite providing detailed information, compromise plant integrity and disturb the surrounding environment. Recent technological advances have enabled the application of non-destructive methods, such as ground-penetrating radar (GPR) and electrical resistivity tomography (ERT), allowing in situ characterization of root systems without physical disturbance. These techniques provide valuable insights into root architecture under natural field conditions, although their performance is strongly influenced by soil properties, particularly texture, with clay-rich soils limiting data reliability. This study aimed to map the root architecture of eucalyptus trees by integrating non-destructive geophysical data with machine learning techniques across different soil types. The research was conducted in eucalyptus plantations (Eucalyptus spp.) located at the Federal University of Viçosa campus and in a commercial plantation in Belo Oriente, Minas Gerais, Brazil. GPR surveys were performed using a SIR-3000 system with 400 MHz and 900 MHz antennas. All transects were geoReferencesd using a geodetic GPS. ERT surveys were conducted using a 4-Point-Light 10W resistivity meter in a dipole–dipole configuration, with 40 electrodes spaced at 0.5 m, reaching a maximum investigation depth of 3.8 m and applying 13 progressive investigation levels. Method validation was carried out through the careful excavation of six representative trees, whose root systems were scanned in three dimensions using terrestrial laser scanning. Data integration and analysis were performed using machine learning techniques implemented in the R environment. The results demonstrated the potential of the integrated approach for characterizing eucalyptus root systems. GPR data were more effective in detecting root structures, while ERT data were primarily associated with soil physical properties. The 400 MHz antenna showed the best performance in identifying the depth range containing the largest root volume. Higher correlations with laser scanning data were observed in medium-textured soils, highlighting the strong influence of soil class on method performance.

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# Exploring the controlling factors of soil spatial heterogeneity with high-resolution environmental covariates:A case study of wildfire-affected and reclaimed artificial forests in Japan

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**ABSTRACT**

Soil spatial heterogeneity is driven by complex interactions, like pedogenic and hydrological processes, serving as a key factor in nutrient cycling and vegetation dynamics. While anthropogenic (e.g., construction) or natural (e.g., wildfire) disturbances initially disrupt these spatial patterns, subsequent pedogenic processes may gradually modify them. However, the specific environmental drivers controlling spatial dependence, particularly on the micro-scale, remain poorly understood. Traditional survey methods often fail to capture the fine-scale heterogeneity of micro-topography and vegetation structure regulating this soil spatial dependence. Terrestrial Laser Scanning (TLS) was employed to obtain the high-resolution environmental indices that may drive spatial dependence in soil physicochemical properties. This study compares two different sites: (1) artificial greenery areas, representing a soil chronosequence, and (2) a forest ecosystem recently affected by fire, representing a short-term response to the disturbance. This approach can allow us a quantitative analysis of the relationship between soil spatial structure, micro-topography, and vegetation.

The study sites are anthropogenic greenery areas constructed with subsoils of Andosols (9, 15, and 52 years old) and two forest sites with eight months post-fire, classified into high-severity and low-severity plots. Soil samples collected via grid sampling were analyzed for basic physicochemical properties (pH, electrical conductivity, total carbon (TC), and total nitrogen (TN)) and site-specific properties (e.g., pyrophosphate-extractable aluminum (Alp), iron (Fep), and carbon (Cp,) and magnetic susceptibility). High-resolution environmental covariates, specifically micro-topographic and vegetation structural indices, were calculated using 3D point cloud data, obtained by TLS. Spatial dependence was evaluated via semivariogram analysis, and correlation analysis was conducted to clarify the relationship between soil properties and the covariates.

Topsoils in anthropogenic greenery areas (0-5 cm depth) exhibited significant spatial dependence of TC and Cp, reflecting humus accumulation and A-horizon development, whereas subsoils (5-30 cm depth) showed random distributions. Regarding wildfire-affected soils, preliminary results indicate that water content in surface soils (0-2 cm depth) was correlated with elevation, with higher water content at slope bottoms. This presentation will further elucidate the spatially varying relationships between these soil physicochemical properties and high-resolution environmental indices, utilizing Geographically Weighted Regression (GWR).

# The Uncertainty of the Carbon Sequestration Potential of Arable Soils in European Russia at different scales

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**ABSTRACT**

Soils are the largest terrestrial reservoir of organic carbon. For the Russian Federation, which has vast and highly varied arable land, obtaining accurate, detailed estimates of sequestration potential is particularly important, given the challenges of meeting climate commitments and developing the domestic carbon credit market. Standardised methods, such as those proposed by FAO as part of the GSOCseq project, are widely used internationally to assess carbon sequestration potential. This approach uses dynamic models (RothC) and relies on global climate databases and universal algorithms to calculate net primary production (NPP), such as the MIAMI model. Although this approach ensures that results can be compared globally, it significantly limits consideration of regional and local specifics relating to agricultural practices, levels of intensification and local soil and climate conditions.

The level of detail in the model can be increased by using national data. To this end, a methodology has been developed to calculate NPP based on national statistical data at the municipal level. Using data on crop yields and cultivated areas, the biomass of plant residues and carbon input into the soil were calculated.

A 20-year forecast of soil organic carbon stock dynamics was produced using the RothC model. The RothC model has several advantages: it is accessible; it is compatible with GIS spatial data; and it is scalable from regional to global levels. This study focused on arable soils in the European part of Russia and considered different spatial levels: global, soil and ecological zones, regions and municipalities. Examples at the scale of a field were also considered. The uncertainty was estimated using the Monte Carlo method.

When using estimates averaged over time and space, the mapping uncertainty of carbon stocks and their changes have varied from 14% to 20%. Considering actual yields and the structure of cultivated areas at a municipal level enabled us to identify significant variability in agroecosystem productivity and, consequently, soil sequestration potential. There was high spatial differentiation in the carbon sequestration rates of municipalities located close to each other within the same natural zone or district. Estimates were more uncertain when the territory's natural potential was lower and the productivity of the agroecosystem depended on the degree of territory intensification.

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# Field-scale prediction of black soil thickness based on wavelet decomposed components and multi-model validation

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## ABSTRACT

Black soil thickness, as one of the core indicators in black soil research, is critical for soil organic carbon storage estimation, soil erosion, and soil health, and its spatial distribution serves as an important foundation for black soil research. Previous studies on black soil thickness mapping have mostly focused on large scales or watershed scales. In Northeast China, the rolling hill topography leads to considerable spatial variability in black soil thickness at the field scale. However, existing research has paid relatively little attention to the field scale. This study was conducted in a 13-ha agricultural field in Hailun city, Northeast China. It utilized unmanned aerial vehicle (UAV) data to acquire topographic and surface soil color information of the field. Discrete wavelet transform (DWT) was applied to decompose terrain index and soil color covariates into approximation and detail components at multiple scales (including 1 m, 2 m, 5 m, 10 m, 20 m, 30 m and 50 m). Optimal scales were selected based on the Pearson correlation coefficient with black soil thickness, with scale optimization performed separately for original variables, approximation components, and detail components. The maximum relevance and minimum redundancy (mRMR) method was used for feature selection. The 10 best features were selected, and 10 models were employed for mapping. The results show that surface soil color covariates improved the accuracy of black soil thickness mapping, $R^2$ improved from 0.16 to 0.20 in the extremely randomized trees model (ERT). Notably, the incorporation of DWT components led to substantial accuracy improvements. Among these models, the ERT model achieved the best prediction accuracy among 10 models, with RMSE of 0.16 m and $R^2$ of 0.56 in leave-one-out cross-validation. The incorporation of DWT components increased $R^2$ from 0.20 to 0.56 compared to models using only original variables. This finding highlights that microtopography exerts a stronger control on black soil thickness distribution at the field scale than at regional scales, due to its influence on localized erosion, transport, and deposition processes. The integration of DWT analysis with optimal scale selection proves effective for extracting microtopographic features relevant to field-scale black soil thickness mapping.

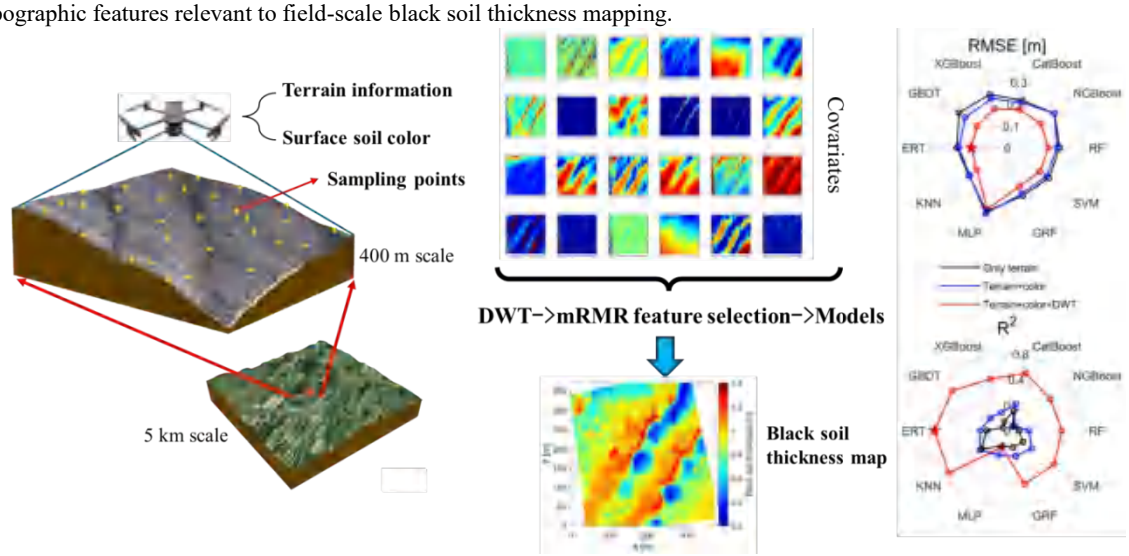



Fig. 1. Graphical ABSTRACT

**Keywords**
Black soil thickness, Soil mapping, Field scale, Machine learning.

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# Climate Variability: Bridging Time Scales in Soil Formation Analysis

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**ABSTRACT**

When studying soil formation, it is essential to have paleoclimate data that is both regular and detailed in terms of temporal resolution. While such data can be readily acquired from paleoclimate modeling initiatives, these model outputs do not always accurately capture climate variability and its primary drivers. Indirect paleoclimate indicators—such as those derived from pollen analysis or the measurement of annual tree rings—offer reliable information about climate variability. However, these indicators vary in their temporal resolution, and none comprehensively cover the entire timeline of soil development at a fine resolution. Specifically, fine-resolution data are available only for shorter periods, whereas longer periods typically have coarser resolution.

In this study, we aim to bridge the gap between different temporal scales by identifying the main modes of climate variability using a combination of paleoclimate indicators with differing time scales in the forest-steppe region of Central European Russia, where Chernozem soils are formed. Our novel data sources include GDGT (glycerol dialkyl glycerol tetraether) biomarkers and deuterium biomarkers extracted from peat sediments and soil profiles.

To build our analysis, we utilized time series derived from the TRACE project's paleoclimate modeling data using the CCSM model. This involved decoding and converting the data into time series for specific grid cells within our study area. Through singular spectrum analysis, we identified three main variability modes. Subsequently, we refined the modeled time series using model-data fusion techniques to yield a more realistic portrayal of each mode and generated homogenized timeseries.

The resulting time series of evapotranspiration, precipitation, and temperature at the soil boundary were then employed to define the boundary conditions for the SoilGen model, which simulates soil genesis. This integration enabled us to estimate various processes, such as weathering rates, soil formation, clay migration, and carbon accumulation, during both humid and dry climatic periods relevant to Chernozem soils. The rates of these processes are particularly important for practical applications in soil science and management.

**Acknowledgments**

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# Podzols of the north of Western Siberia – the bridge between modern soil formation and paleocryogenesis

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**ABSTRACT**

Podzols are widespread intrazonal soils, formed from different parent materials in diverse regions. The variety of factors contributes to their heterogeneity in morphological and chemical properties. Paleocryogenic phenomena, widespread both globally and in Russia, have a special impact on modern soil formation, including podzolization. In the past, 95% of Russia's territory was covered by permafrost, and at present the soil cover is largely associated with paleocryogenesis.

The purpose of this research is to assess the influence of paleo- and modern cryogenesis on the podzol formation. The objects are podzols of the discontinuous permafrost zone of the north of Western Siberia (Russia, 65°18'46"N 72°52'567"E). Currently, permafrost is absent in the forest ecosystems studied, although this area froze repeatedly during the Holocene. Traces of this are now widely present at various levels. Paleocryogenesis is expressed as the paleocryogenic relief (PCR) in the landscape and as ice-wedge pseudomorphs in the soil profile. PCR is presented as polygonal alternation of hummocks and depressions, height differences of 1-3 m. The pseudomorphs, formed after ice-wedge melting, are presented at a depth more than 0,5 m and are filled with loam, hosted in sand parent material. In the relief above them depressions of the PCR are formed, repeating a paleocryogenic net. A distinctive feature of soil formation in the study region are cryoturbations of various times, forms and severity, forming a complex heterogeneous parent rock, introducing specificity into soil formation.

The dominant soils in forest ecosystems are Podzols. Soil complexes are confined to PCR: Albic Glossic Podzols are formed along a net of depressions, and Entic Podzols on hummocks, the average thickness of the E horizon respectively is 45 ± 9.2 and 4.2 ± 0.8 cm. Soils in depressions are mainly sandy, while on the hummocks the loamy texture changes to sandy at a depth of 40 cm. A distinctive feature of podzols are the thick tongues of the albic horizon, occurring most commonly in depressions and developing along pseudomorphs. The average thickness of the tongues is 51.2 ± 13.8 cm, with a maximum of 150 cm. A field filtration experiment showed that the tongues are associated with the main flows of soil solutions, redistributed under the influence of paleocryogenic phenomena.

Chemically, all soils are Podzols, with accumulation of oxalate-extractable Fe and Al in the spodic horizon, but the iron balance between the spodic horizon and the bedrock is negative. Paleocryogenic loamy pseudomorphs can serve as an additional source of Fe and Al, enhancing the podzol formation process.

Morphology of albic horizon and its distribution in northern Western Siberia is associated with paleocryogenic phenomena. Paleocryogenesis forms landscapes, patterns the soil cover, redistributes soil solution flows across the relief and within profiles, and significantly transforms the evolution and morphology of podzols.

# How Periglacial Past Affected the Evolutionary Pathways of Holocene Temperate Soils: Northern Part of the East European Loess Belt

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**ABSTRACT**

Modern (i.e. Late Holocene) soils of the East European loess belt often expose relict features associated not only with their Holocene evolution, but with pre-Holocene processes. The impact of the pre-Holocene stage on formation of Luvisols and Phaeozems is still actively debated. However, evidence from stable geomorphic surfaces of the watersheds prove the continuous soil development unaffected by major denudation/accumulation events such as glacial erosion of significant loess deposition at least since the Late Glacial (12-15 ka). A consistent model of pedogenesis requires both an identification of the past (relict) profiles in the welded soil body and an evaluation of soil formation as a continuous process. To achieve this goal, we conducted studies of the upland soilscapes in the marginal zone of Moscow (MIS 6) glaciation at different scales. Applying a complex methodology including UAV and geophysical surveys we revealed the organization of polypedons. The heterogeneity of soil cover is predetermined by polygonal thermal-contraction cracking during cold stages of MIS 2. As polygonal landforms almost disappeared by the end of MIS 2, the residual polygonal geological structure of the soil-forming deposits controlled pedogenesis throughout the Late Glacial and Holocene. For example, preferential flows seem to be associated with the former troughs and nodes of polygonal nets promoting the vertical translocation of solid matter. As a result, in these positions morphological features as prismatic structure, clay and silt cutans, etc.) are usually more pronounced and profound. $^{14}C$ ages of the organic matter in clay papules along the Younger Dryas cryostructures reach 16 ka cal BP while ages of humified matter filling the cryostructures reach 13 ka cal BP. Thus, the pre-Holocene stage not only prepared the substrate for interglacial pedogenesis, but also started some of the main soil-forming processes that continue to this day.

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# Informational role of buried Podzols in reconstruction of Holocene pyrogenic activity: a case study of Northern European Russia

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**ABSTRACT**

The regional-scale pyrogenic events had sharp changes of frequency and intensity in the Holocene, that proves sediments studies (Novenko et al., 2021). The studies of soil pyrogenic paleoarchives in geomorphic traps (e.g., karst holes) allows to investigate the wildfires spreading at the local scale. The findings of macrocharcoal particles (>125 μm) in these traps, laterally transported only for hundreds of meters after fires, prove this issue (Matthews J. A., Seppälä M., 2014). The objective of this study is to reveal the informational role of soils for the supplement of the Holocene pyrogenic activity paleo reconstructions by local scale data.

The studies were carried out at the South-East of Kola Peninsula ("Keiva II) and Upper-Kuloy Plain ("Pinega basin"). Totally, 143 radiocarbon dates ($^{14}$C dates) were obtained from macrocharcoal particles extracted from the soil pyrogenic archives. Graphitization and target pressing were conducted in the Radiocarbon Laboratory of the Institute of Geography RAS (Moscow, Russia) and $^{14}$C AMS measurements were done at the Center for Applied Isotope Studies of the University of Georgia (Athens, USA). Dates from the "Keiva II" and "Pinega basin" are substantially complement. The oldest $^{14}$C dates relate to the Early Holocene (≈ 10.5 ka cal BP). The first increase in the probability pyrogenic periods was detected in interval 9.8-9.6 ka cal. The second increase take place in interval 1.2-0.8 ka cal BP and until the Present time. The "Keiva II" object has the increase in the probability pyrogenic periods in the Middle Holocene (Mergelov et al., 2024).

These dates prove, that the frequencies of wildfires and the quality of pyrogenic activity records can be quasi-constant at the local scale owing to the following factors: 1) the pine taiga with lichen-moss ground cover; 2) the geomorphic traps, accumulating erosional material and 3) the drained sandy soils (Albic Podzols), compile of pyrogenic archives.

**Acknowledgments**

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# Paleosols and Their Classification in US Soil Taxonomy

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**ABSTRACT**

Paleosols (ancient soils) have many definitions, dependent upon the discipline defining them. In soil science, a paleosol may be defined as an ancient soil (often with advanced development) that A) formed under relict soil forming conditions, B) is insulated from many current surficial soil genesis processes by a more recent deposit, or C) is old enough to have either been lithified or is beneath a lithified layer. There are soils on ancient landforms that may be older than paleosols, so age alone is not a defining factor. There is no minimum age for a paleosol but it is logical that they are older than Holocene age. Paleosols are not specifically identified in Soil Taxonomy. Paleosols type A are found within the Aridisols and Oxisols orders and in six 'Oxic' and 'Torroxic' subgroups. Soils in 14 'Pale' great groups, 10 'Kandi' great groups and five 'Abruptic' subgroups are old soils but do not always fit one of the three paleosol types above. Diagnostic horizons and characteristics that take a long time to develop include petrocalcic, petrogypsic, and duripans, abrupt textural change at the top of an argillic or kandic in a moisture limited environment, and unusually thick argillic or kandic horizons with minimal (< 20%) relative cutback of clay content within 150 cm, with either albic material or redder colors required (Alfisols) or optional (Ultisols). Paleosols of type B are not typically found in floodplains, on anthropogenic landforms, or in areas of ongoing disturbance and deposition. Paleosols type B are not readily identified in Soil Taxonomy, because after the younger deposit develops diagnostic horizons throughout, the entire profile is classified. At that point the soils are largely in 14 'Pale' great groups, 10 'Kandi' great groups, or five 'Abruptic' subgroups. Paleosols type C are sometimes called 'fossil soils' and are not classified using *Soil Taxonomy* but have been identified by geologists and paleontologists. A review of the types of paleosols and the specific taxa that may identify paleosols will be presented.

# Geochemical signatures (pXRF) of polygenetic soils in the Cerrado-Caatinga transition, Piauí, Brazil

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**ABSTRACT**

The expansion of the agricultural frontier in the Cerrado-Caatinga transition (MATOPIBA) in Brazil is advancing over pedologically complex landscapes, whose polygenetic origin is often underestimated. Understanding the superposition of pedogenetic events is crucial for sustainable management, but traditional methods (morphology, physics, and chemistry) can be inconclusive. This study aimed to use portable X-ray fluorescence (pFRX) as a high-resolution tool to decipher pedogenesis and identify parent material provenance in a representative catena in the Alto Rio Gurguéia Basin, State of Piauí, Brazil. Six soil profiles (two Fluvisols, two Gleysols, one Solonetz, and one Cambisol) were described, and samples from all horizons (fine earth fraction) were analyzed by pFRX (Bruker TRACER 5g). Elemental geochemical data (K, Ca, Ti, Fe, Zr, etc.) were integrated with morphological, physical, and chemical data to validate pedogenetic interpretations. The pFRX results provided conclusive geochemical evidence that detailed the landscape's history Variation in the Ti/Zr ratios (from 1137/2005 ppm and 55/96 ppm, respectively) indicated a lithic discontinuity in a Dystric Arenosol (Thaptoferralic, Profondic, Ochric) (FG15). According to the chemical composition, the ferralic horizon was buried by sandy materials derived from Si-richer rocks. In the Abruptic Luvisol (FG05), extremely high K contents (increasing from 1307 to 5859 ppm at depth) acted as a geochemical "fingerprint," confirming the Longá Formation pelites as the parent material and source of the high Na levels (ISNa > 47%) that enhance clay translocation. On the alluvial plain, pFRX differentiated geochemically distinct Gleysols: the Gleyc Vertisol (FG04) was rich in Fe (>20,000 ppm) and Ca (>3300 ppm), aligning with its high CEC (17.97 cmolc/dm³); whereas the Sodic Gleysol (FG09) was extremely poor in Ca (<362 ppm), demonstrating distinct pedogenetic pathways (vertic vs. sodic) within a short distance. The pFRX analysis was decisive in validating the occurrence of paleosols (2Ab horizon in a Eutric Fluvisol FG13) and in differentiating depositional layers within the Fluvisols. We conclude that pFRX geochemistry is an essential and rapid tool that, when integrated with classic pedology, enables the confident decoding of the complex history of polygenetic landscapes and is fundamental for land-use planning in this agricultural frontier.

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# Deciphering the Construction of the Ancient City of Palenque and its Effects on the Landscape

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**ABSTRACT**

The ancient city of Palenque, in the Mayan territory, was established in a strategic position between the piedmont of the Sierra de Chiapas and the alluvial plain of the Michol River, becoming a dominant city during the Classic period (250-900 AD). During its construction, landscape modifications were made on different scales and intensities. In this work, we present a combined study of natural and urban soils together with technogenic materials, and geomorphological analysis based on Lidar survey. The natural soils and Technosols (backfills) properties were determined to recover different aspects of the soil memory about the environment. The geomorphological approach revealed various landscape modifications, including terrain leveling, the construction of structures, and the diversion of rivers and streams. Due to the diversion, changes in the water and sediment supply caused the modification of the alluvial fan configuration as well as the location of the travertine outcrops. Regarding the pre-Palenque soil cover, our study demonstrates the presence of yellowish, sandy-silty soils derived from Cretaceous sandstones around the site, which is also present beneath the constructions. This soil distribution differs from that of nearby archaeological sites, where limestone produces Rendzinas and Luvisol-like soils. Finally, our study showed the use of similar materials at different construction stages in the backfills (bones, shells, limestones, stucco, ceramics, charcoal, soil, and travertine); however, there were differences in their proportions. The initial stage, dated to 200-350 AD (based on a radiocarbon date from organic matter in the buried paleosol underlying the studied building), was characterized by the primary use of soil fragments. The final stages documented a significant use of limestone and travertine.

**Keywords:** soils, backfills, travertine, geomorphology, sandstones

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# New findings from the Baix loess profile (Rhône Rift Valley, southern France) in the climatic transition zone between Central and Southern Europe

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**ABSTRACT**

Loess paleosol sequences (LPS) are archives of paleoenvironmental changes over time. Comparing different LPS enables the detection of spatial differences in paleoenvironmental conditions for the same temporal period. Here we present the Baix loess profile on the western shoulder of the Rhône Rift Valley in southeastern France at 44°42'36" N and 4°43'21" E. It shows an approximately 14 m thick LPS, which is of particular importance given the location of the Baix profile in the transition zone from the current temperate to the Mediterranean zone. We argue that the LPS exposed in the Baix profile represents a previously missing link between the comprehensively analyzed LPS of the temperate zone in the north (northern France, Alsace, Germany) and those of the Mediterranean region in the south (southern France, Catalonia, Italy, Croatia). We analyzed Baix using common paleopedological methods in combination with OSL dating. In addition, macroremains were isolated by flotation and sieving. Their examination under a binocular resulted in 79 charcoal pieces, approx. 2,100 mollusk shells, approx. 450,000 earthworm calcites, and 250 volcanic ash particles, probably from the Chaîne des Puys (French Massif Central). These proxies provided valuable additional evidence of fires and trees, and supported our paleoenvironmental interpretations.

The base of the profile is a sequence of reddish Btg horizons of an Eemian to early Würmian (MIS 5) pedocomplex. This basal part ends with an erosional unconformity, which is overlain by a layer of relocated soil material and loess, containing volcanic ash and charcoal from deciduous trees. The overlying loess (MIS 4) exhibits a sequence of Bw horizons. The upper boundary of this sequence is very diffuse, indicating that these Bw horizons must have formed synsedimentarily, during increasing loess deposition. Above, a truncated Calcic Cambisol from the Middle Würmian (MIS 3) has been preserved. Unusually large loess dolls beneath indicate that considerable amounts of carbonate have been leached from this paleosol. The Calcic Cambisol is very similar to the Middle Würmian paleosol remains in the Collias loess profile, located 87 km further south, in today's Mediterranean climate. The top of the Middle Würmian Calcic Cambisol is marked by another erosion unconformity. Above, several slightly brownish horizons follow, developed in slope-wash loess (MIS 3). The lowermost one contains volcanic ash and charcoal from Pinus and deciduous trees. The uppermost section of the profile (MIS 2) does not exhibit any paleosols. Apparently, the sedimentation rate was too high compared to the soil formation rate during this period, and there was no permafrost that would have allowed for the formation of any Reductaquic Cryosols that are commonly observed in similar stratigraphic position in the LPS of Central Europe.

# Earthen archaeological sites as archives of information on the evolution of soils and paleoclimate of the second half of the Holocene, dry steppe zone, Southern Cis-Urals, Russia

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**ABSTRACT**

The challenges of conducting paleoclimatic reconstructions in the Southern Cis-Urals, a steppe zone in Russia, based on the study of paleosols buried beneath burial mounds (kurgans) are in the focus of this research. Over the past 30 years, one settlement, approximately 20 kurgan cemeteries, and 90-100 kurgans representing the cultures of the Bronze Age, Early Iron Age, and Middle Ages we have studied in the region. This examines pedochronosequences' features over long (>500 years) and short (≤100 years) timescales. The properties of Chernozems and Haplic Kastanozems can shift in <100 or 100-200 years, with varied directions of changes during Holocene climatic changes. When studying both long-time and short-time pedochronosequences, the set of soil properties required for paleoclimatic reconstruction is identical and includes the degree of mesofauna activity within the soil profile, morphological and chemical indicators of the humus profile (boundary of the humus horizon and its color, organic carbon content) and salinity (content of carbonates, gypsum and the appearance of their accumulation in the profile, parameters of water extract), the content of exchangeable bases, in particular Na, the value of magnetic susceptibility, the radiocarbon age of organic carbon and carbonates, and their isotopic composition. Work in short-time pedochronoseries is carried out at the limit of the temporal response of soil properties to climatic changes, which allows us to avoid errors in determining the direction of climatic changes, as well as to conduct a chronological analysis and propose a relative (earlier-later) order of kurgan construction in the cemeteries of representatives of the same archaeological culture. For the dry steppe Cis-Urals, a climate change scheme over 7,000 years, and soil subtype dynamics are presented.

The earliest kurgans of the Yamnaya culture (6000-5300 years ago) were created in extremely arid conditions, resulting in a shift from Haplic Chernozems to Calcic Chernozems. Between 5300 and 4300 years ago, the climate became gradually wetter. The area of the Haplic Chernozems broadened and shifted to the south. The analysis of Subboreal soils, which date back to 3900-3500 years ago and are found buried under the kurgans of the Srubnaya culture, shows that between 3900 and 3800 years ago, the driest climatic conditions were dominant. After the aridization stage, a period of climate softening began, marked by a gradual increase in humidity that continued until the end of the Srubnaya culture (3600-3500 years ago); Calcic Chernozems shifted further south. Frequent climate changes marked the Subboreal and Subatlantic periods' Holocene border (2700-1600 years ago). The shift of Calcic Chernozems and Haplic Kastanozems was recorded in two timeframes: 2700-2400 years ago (north) and 2400-2200 years ago (south). Around 650-600 years ago during the Middle Ages, the climate became more humid and mild, which changed Calcic Chernozems to Haplic Chernozems. The unresolved issues are presented at the end, along with the periods lacking geoarchaeological data.

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# Bronze Age kurgans as a complex paleoarchive: data from paleosoils and kurgan constructions in the steppe zone of Russia

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**ABSTRACT**

Geoarchaeological investigations were conducted at four key sites within the steppe region of Russia: Krasnodar region (kurgan 1 of the Beysuzhek IX cemetery and the Shumny kurgan), Stavropol region (Essentuksky 1 kurgan), and Orenburg region (kurgan 1 of the Boldyrevo IV cemetery). Geoarchaeological studies of paleosols buried under burial mounds/kurgans and the kurgan constructions (KCs) have been carried out with the aim of determining and comparing properties of paleosols and the material of KCs, conducting paleoclimatic reconstructions, as well as obtaining knowledge on the technology used for kurgans building. The kurgans of various Bronze Age cultures have been studied in the steppe area of Russia as a single system "kurgan constructions – paleosols". The research has been carried out comprehensively: the main technologies for building of a kurgan have been identified, and the properties of paleosols and materials of KCs have been compared. This approach significantly increases the reliability and validity of the conclusions obtained, since the object of study is not only buried soils, but also kurgans themselves, the material for the construction of which was collected from the surroundings of a large nearby area.

Micromorphological and physicochemical analyses indicate that the kurgans were predominantly constructed from locally sourced soils, with minimal anthropogenic admixture. For all four studied kurgans, a comparison of the technical and technological approaches used by ancient people for the building of monumental constructions of earthen architecture has been made. Both similarities and differences in the building approaches of the studied kurgans have been revealed.

Based on a combined analysis of physicochemical and morphological data from paleosols, surface soils and materials from KCs, three stages of changing climatic conditions during the Bronze Age in the steppe area of Russia have been identified. An aridization phase during the Atlantic period (AT-3), 5700–5500 years ago, across the East European Plain steppe zone. An aridization phase during the early Subboreal period (SB-1), 4300–4200 years ago, specifically in the Kuban-Azov Lowland and Trans-Kuban Plain.

A humidization phase during the late Subboreal period (SB-3), 3500–3000 years ago, documented in the Trans-Kuban Plain.

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# Pedogenic Response to Holocene climatic fluctuations in the Caucasian foothills (Dagestan, Russia).

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**ABSTRACT**

The buried and surface soils of the Bronze Age settlement «Zidyan-Kazmalyar» (Dagestan, Russia) were studied. The results of morphological and analytical studies revealed significant differences between the background and buried soils. The studied soil profiles exhibit a complex structure, indicating stages of development and the influence of various factors. Buried soils at various depths indicate stable environments, while the presence of redeposited material indicates stages of intensified slope processes.

The use of the soil chronosequence method allowed us to identify differences in the properties of soils formed at different times but in the same area. The surface soils were classified as *Calcic Kastanozems (Aric, Humic, Loamic)*, with a well-developed profile and contain 2.5% TOC in the upper part of the profile. Despite the age of the burial (about 5 thousand years ago according to archaeological finds), 1.5% of TOC and dark humic horizon was preserved in the Bronze Age soil, which indicates high original content of organic matter. We suggest that buried soil of the Bronze Age formed during a relatively warm and humid climate. These conditions were favorable for the development of a rich steppe soil, leading to accumulation of organic matter and the formation of a well-differentiated soil profile. Increased moisture is indirectly indicated by the clearly visible profile of the stream channel at the foot of the slope. The formation of such a well-developed profile requires a long period without catastrophic erosional events. Transition to a cooler climate with fluctuations in humidity was recorded in the spore-pollen spectra of the Dagestan swamps [Ryabogina et al., 2019].

The soil, which dates back to approximately the Mesolithic era, has a poorly developed profile with a distinct humus and carbonate horizon and also contains gypsum inclusions. The abundance of gypsum, which is not found in other soils, and the poorly developed profile indicate an extremely arid climate that existed when this soil was buried. Physico-chemical analyses of soils, as well as phytolith and spore-pollen analyses, complement the paleoecological information about this settlement.

**Acknowledgments**

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# Acid sulphate pedogenesis of the geological past of the Earth and beyond it

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**ABSTRACT**

The talk covers the case study of Mid-Devonian (Eifellian) paleosol developed from rhyolite tuff (Alekseeva et al., 2023; Wang et al., 2025) and three paleosols from the weathered roof of Precambrian basement. The latter is presented by ferruginous shales and quartzites. Paleosols were sampled on the territory of actively excavated quarries. All rocks contain pyrite. The multidisciplinary study covered geochemistry, bulk and clay mineralogy, micromorphology, iron-mineralogy (XRF, XRD, SEM-EDX, Moessbauer spectroscopy). Based on obtained data paleosols were attributed to analogues of modern acid sulphate soils. Such soils developed from deposits containing sulfides. The sulfuric acid – a product of sulfides oxidation, provides pH below 4 which promotes the aggressive chemical weathering. The products of sulfides oxidation are gypsum, Fe-sulfates, Fe-oxides. Due to the numerous possible sources of sulfides (as natural as anthropogenic) acid sulfate soils are azonal. In our days they cover about 1% of the Earth`s territory. Paleosols of this type are among the first appeared. The oldest sulfate containing (kieserite, barite, gypsum) paleosols are Archean – 3.2-3.7 Ga. The remote study of Mars deposits showed that their principal chemical element is sulfur. The deposits are cemented by Mg-, Ca-, Na- and Fe- sulfates and Fe-oxides. This mineral association indicates the distribution of acid sulfate soils beyond the Earth. Martian paleosols are Archean and were arid (Retallack et al., 2023). All paleosols of the given study were developed under rootless primitive vegetation. Soil development was primarily carried out via chemical weathering with a pyrite oxidation as a trigger. The paleosols at the roof of Precambrian basement did not develop the continuous soil cover. Their specific feature was the predominantly below surface (~ 15 cm deep) transformations with the negligeable transformations of the topsoil. Such characteristics puts these paleosols on a par with epilithic/endolithic systems. The paleosol on volcanic material created the cover which thickness depended on the relief of the basement. The transformation of the parent rock affected the whole thickness, but had the localized character and was not accompanied by formation of distinct soil horizons. Present data reveals the spreading of acid sulfate pedogenesis in former geological epochs. Reconstructions of paleoclimate based on geochemical data showed that being gypseous, paleosols nevertheless were developed under humid climate.

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# Indicators of the paleoecological situation in the Volga region soils

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**ABSTRACT**

Several soil sections with cultural layers in settlements of different parts of the Volga Valley - the Upper, Middle and Lower Volga regions - were studied to determine the most informative soil properties for paleoreconstruction of soil formation conditions. The aim of the work was to identify the most informative inertial soil properties based on an analysis of chemical and physical properties of soils.

The isotopic composition of organic carbon of soils, the granulometric composition of soils, the gross chemical composition of soils, specific magnetic susceptibility were chosen as the most informative properties.

The isotopic composition of organic carbon and the radiocarbon age (or relative age based on archaeological data) of soils showed that during the Early Holocene, the δ13C isotope ratios were lightweight (wetter conditions), the proportion of the heavy isotope C13 increased during the Middle Ages (moisture decreased), and the values became even heavier during the Little Ice Age (increased aridization), and have become lighter again for modern times (wet conditions).

The granulometric composition of soils and coefficients calculated based on it – sorting and average diameters of sandy components – have become indicators of the genesis of soils. Most of the studied soils had deluvial and proluvial genesis, indicating the activity of water flows during the formation of profiles.

The values of magnetic susceptibility and the paleoprecipitation calculated from them (for soils of the dry-steppe zone) showed maximum values in buried horizons of the Early Holocene, medieval layers, in solonetzic horizons and in surface humus horizons. This indicates increased moisture during these periods and in modern times, and the maxima in the solonetzic horizons are also the result of the solonetzic process: a silty fraction accumulates in them, to which magnetic particles are confined.

The correlation of the analyzed properties allows us to conclude that the formation of Early Holocene soils exposed in the Middle and Lower Volga regions in humid conditions. By the Boreal period of the Holocene, the climate had become drier; horizons and cultural layers of the medieval age were formed in warm and moderately dry conditions of climatic optimum; the Little Ice Age began with increased processes of climate aridization, including due to increased anthropogenic activity. By modern times, the humidification of the climate in the Volga region is increasing. As for the late Holocene soils of the Upper Volga region, their properties of the medieval climatic optimum and the Little Ice Age are manifested by a decrease in moisture.

Thus the most inertial indicators have been selected that preserve information about climatic rhythms – the isotopic composition of soil organic carbon, specific magnetic susceptibility, and granulometric composition.

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# Paleosols as a key for piecing together the past climates and the intricacies of soil processes

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**ABSTRACT**

Paleosols are the most important paleogeographic records which reveal paleoclimate and palaeoecology. Integration of all paleopedospheres in our research region allows us to create a nearly continuous depiction of Earth's lithosphere history. The key goal of our team's research is to analyse mineralogical and biogeochemical solid-phase records of the soil matrix to extract quantitative parameters for paleoenvironments, including climate and vegetation, throughout a broad temporal period encompassing the Holocene, Pleistocene, and Paleozoic. Numerous Quaternary paleosols were discovered in steppe regions beneath ancient monuments (mounds, kurgans, earthen fortifications), spanning the middle and late Holocene. The scientific approach involved a comparative investigation of the morphological, chemical, magnetic, and mineralogical characteristics of buried paleosols of varying ages and their contemporary counterparts. The content of soil magnetite was used as a “magnetic record” of the previous environmental conditions of the steppes, which allowed quantitative reconstructions of the climate, as well as a quantitative assessment of the shift of natural boundaries during the late Holocene in the south of the East European Plain, caused by climatic variations (Alekseeva 2007, Alekseev et al. 2020). Statistical analysis of climatic dependencies of changes in magnetic susceptibility in modern steppe soils of the south of the East European Plain demonstrated, albeit with certain limitations, the possibility of estimation the precipitation and the De Martonne aridity index (IDM) of past eras (Alekseev et al. 2023). A retrospective analysis of organic matter of soil clay fractions, incorporating NMR spectroscopy and $\delta^{13}C$ data from contemporary soils and Quaternary paleosols, additionally facilitates refinements to paleoclimatic reconstructions. Climate factors over the last 5,000 years in East European part of Russia were reconstructed using connections with magnetic soil properties, clay mineral composition, and soil carbon isotopic signatures. Similar approach was employed for the examination of Pleistocene loess-soil complexes (Alekseev, Alekseeva 2024). Bulk chemical and mineralogical composition of pre-Quaternary paleosols were utilised to reconstruct paleoclimatic and paleoenvironmental conditions. The geochemical and mineralogical characteristics of biogenic transformations of sediments and paleosol formation in the European region of Russia and the Spitsbergen archipelago during the Devonian and Carboniferous periods, along with the reconstruction of terrestrial ecosystems and climate, will be presented (Alekseeva et al. 2016, Alekseeva et al. 2025, Alekseev et al. 2025, Alekseeva et al. 2026).

# Reading the Quaternary Soil Memory: Quartz Isotope Fingerprints of Aeolian Processes in the Asian Steppe

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**ABSTRACT**

Aeolian dust originating from the arid and semi-arid regions of East and Central Asia is a fundamental component of the Earth's climate system, significantly influencing regional and global atmospheric processes, nutrient cycling in marine ecosystems, and the formation of extensive loess-paleosol sequences throughout the Quaternary. While traditional models have long emphasized the Gobi and Taklamakan deserts as the primary "dust factories," the role of the vast Eurasian steppe remains a critical yet underexplored piece of the paleoenvironmental puzzle. This study adopts the transdisciplinary concept of "soil as memory" to investigate the Asian steppe's potential as a major dust source, utilizing the stable oxygen isotope composition ($\delta^{18}O$) of quartz grains as a robust provenance tracer

To establish a comprehensive geochemical baseline across diverse landscapes, we analyzed surface soil samples from twenty-four strategic sites across the Asian steppe corridor—encompassing regions in Ukraine, Kazakhstan, Mongolia, Xinjiang and Inner Mongolia. Furthermore, to examine the vertical "memory" of these landscapes and their long-term sedimentary contributions, we conducted analysis of four distinctive soil pedons located in key dust-generation zones of Mongolia and Inner Mongolia. These profiles were sampled at multiple depths (including surface and three deeper horizons) to evaluate the temporal continuity and evolution of aeolian deposition within the soil record.

Analytical results demonstrate a clear isotopic partitioning based on grain size: fine-sized quartz particles exhibit significantly higher $\delta^{18}O$ values, indicating a primary origin from low-temperature sedimentary environments—the typical precursors to regional loess deposits. Conversely, coarser quartz grains are associated with lower $\delta^{18}O$ values, linking them to high-temperature igneous basement rocks. This observed spatial and stratigraphic distribution of $\delta^{18}O$ signatures highlights the complex interaction between regional lithology and aeolian processes

Our findings suggest that the Asian steppe provides a unique "memory" of dust transport dynamics, reflecting the seasonal and historical modulation of the mid-latitude westerlies and the East Asian monsoon system. By integrating these isotopic fingerprints with soil pedology, this research offers novel insights into the provenance of Asian loess-paleosol sequences and the broader evolution of Quaternary geosystems in the Northern Hemisphere.

**Key words:** Asian Steppe; Aeolian dust; Oxygen isotopes; Quartz; Dust transport.

# More than a metaphor: soil memory as methodological framework

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**ABSTRACT**

Paleopedology studies fossil soils or paleosols. It is a historical science, or as previously highlighted by Ruellan (1971), the historical branch of pedology. Soil characteristics with paleoenvironmental significance that persist (inheritance or heredity) belongs to the concept of soil memory (Targulian and Goryachkin 2004). The soil memory concept consists in rethinking how information is received, transformed, and recorded in natural bodies through self-organization of unstable dynamic systems. Soil memory, as all scientific concepts, does not manifest in the tangible world; rather, it constitutes a mental construct for comprehending reality. The soil memory is composed of an empirical data set employed to elucidate the outcomes of bio-abiotic system preserved within the geological record. Just as paleontologists do not examine dinosaurs, and archaeologists do not investigate ancient societies directly, but rather focus on material remnants such as fossils and lithic artifacts. Paleopedologists typically do not directly observe actively-forming soils. In sum, paleopedology deals with partial evidence of something that existed or happened in the past. The objects of paleopedology and pedology are similar, however, present distinctions. Nonetheless, analogy, analogical reasoning, and analogical arguments based on extant soils play a key role in paleopedological studies, even in the absence of modern analogs for specific paleoenvironments, such as Archean paleosols. Analogy is defined as inferential processes to establish comparison between selected objects, or systems of objects highlighting their similarity. In analogy, the characteristics of unknown objects are seen in the light of known objects, allowing the establishment of analogical reasoning and emergence of hypotheses that need independent verification. Soil memory has two analogic aspects: (i) analogic explanation, which highlights the most relevant features when compared to other features highlighting causal relationships; (ii) argumentation to evaluate with hypotheses. The dual analogical aspects, we argue, make the soil memory. In the context of soil memory, the concept of uniformitarianism is applied to infer conditions rather than to compare objects or systems of objects. Thus, soil memory may be regarded as a framework for identifying regularities at different scales (not necessarily universal regularities due to local and historical contingencies) in the paleopedological record. The regularities may be seen as models of causal systems, based on the "redescription" and inference of past reality through similarities (both qualitative and quantitative) between objects. Soil memory provides an "experimental context" to emphasize the observed regularities. It is more than a metaphor; it is a methodological framework.

# Paleoenvironmental significance of earthworm aestivation chambers from Cretaceous paleosols ofAraripe Basin, Brazil

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**ABSTRACT**

Aestivation is a key adaptation to environmental stresses, such as seasonal drought. Earthworms, which depend on cutaneous respiration and thus require a moist environment, construct aestivation chambers to avoid desiccation during dry periods. Earthworms are highly diverse and ubiquitous in modern environments , acting as significant ecosystem engineers. Nevertheless, despite their prominence in the soil community and long evolutionary history, earthworm chambers preserved in paleosols are remarkably scarce . The present work provides detailed descriptions of pelleted chambers produced by earthworms preserved in mid-Cretaceous hydromorphic paleosols of the Exu Formation, Araripe Basin, Brazil. The results show that the chambers present sub-circular to ovoid shape with diameter of 20–80 mm. The walls are multilayered, 3–9 mm thick and composed of diverse distinct layers of reddish sub-circular and flattened pellets composed of clay material tightly attached. The chamber itself is filled with sub-circular pellets like those found in the walls. In thin section, the chamber walls consist of multilayered, reddish-brown, inorganic clay linings with incorporated grains. The grains are oriented parallel to the layer and exhibit discrete discontinuities. The walls display a sharp boundary with the surrounding paleosol fabric, defined by a thick clay lining that contains subcircular microaggregates with different sizes of tightly packed clay, and oxides with coarse mineral grains. The quartz grains are oriented inside the aggregates, in some cases different aggregates are attached to each other, forming a grano -striated pattern. Therefore, the lining composed of clay and clayish pellets suggests that the producer lined the chamber with pellets, as ingestion of soil may select the fine fractions of soil. In this scenario, the producer probably encased itself in the subcircular pelleted chamber, a behavior supported by the pelleted texture of the wall. A similar process is observed in the aestivation chambers of extant earthworms, such as Acanthodrilinae sp. and Rhinodrilus alatus. These worms mix clay with mucus and gut content, to construct their chambers, and the mucus secretion contributes to retain water, keeping the worms moist during aestivation. Yet, the aestivation behavior is supported by chambers in paleosols with hydromorphic features that suggest variations in drainage conditions with periods of increased moisture, despite the overall semi-arid conditions of the Exu Formation. Therefore, these chambers indicate that during dry season with lowered water tables, these organisms were forced to construct aestivation chambers, as observed in extant earthworms.

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# Testing the Transferability of Paleosol Geochemical Proxies in Tropical Maastrichtian Climates: Evidence from India

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**ABSTRACT**

The geochemical characteristics of paleosols, particularly weathering indices and elemental ratios, are widely used for quantitative paleoclimate reconstruction in deep-time records. Geochemical climofunctions, such as mean annual precipitation (MAP) estimates derived from the CIA-K and hydrolysis indices, have been especially important for reconstructing past moisture regimes by linking elemental depletions and enrichments to climatic parameters. While these methods have provided valuable paleoenvironmental insights, most widely used calibrations are based on temperate North American soils and assume that soil moisture balance is primarily controlled by precipitation. This assumption limits their applicability in tropical to subtropical regions, where high evapotranspiration strongly influences soil water balance and modifies pedogenic geochemical signals, potentially introducing systematic biases in low-latitude MAP reconstructions.

The humidity-regime model of Gulbranson et al. (2011) attempts to overcome this limitation by integrating both water influx and efflux; however, its performance in tropical paleosols remains poorly evaluated. This regional bias raises concerns regarding the global applicability of standard paleosol-based geochemical proxies. To address this issue, we assess the performance of multiple paleoclimate proxies in tropical, low-latitude Maastrichtian (Late Cretaceous) paleosols from India. We apply the Chemical Index of Alteration (CIA-K), base cation to alumina ratios (ΣBases/Al), and a humidity-regime model to reconstruct paleoclimate conditions.

A comprehensive multi-proxy framework is used to cross-validate geochemical climate estimates with independent evidence from fossil plant assemblages (micro- and macroflora), pedogenic micromorphology, and sedimentological observations. Results consistently indicate a humid subtropical climate with high rainfall and warm temperatures, supported by moisture-loving plant assemblages and evidence for intense chemical weathering. Crucially, this study provides one of the first systematic evaluations of commonly used paleosol-based geochemical proxies and the humidity-regime model in tropical, low-latitude Maastrichtian paleosols. While geochemically inferred MAP values broadly agree with paleobotanical and pedogenic indicators, we demonstrate that North American-derived calibration equations introduce predictable, systematic biases when applied to Indian paleosols.

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# Distribution, characteristics, and formation mechanism of siliceous restrictive layers in the black soil region of Northeast China

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**ABSTRACT**

In recent years, extensive soil surveys have discovered that a special silica-clay composite layer is widely distributed across the black soil region of Northeast China. This layer feature, provisionally termed the siliceous restrictive layer, significantly impedes plant root penetration and soil moisture movement, accelerates slope erosion, and critically threatens regional food security and agricultural sustainability. Despite its ecological importance, the spatial distribution, physicochemical characteristics, and formation mechanisms of this layer remain unclear.

This study integrates systematic field investigations with machine learning modeling to address these knowledge gaps. The 922 soil profile records and 21 environmental covariates were compiled, and a random forest algorithm (Kappa coefficient = 0.42) was used to delineate the siliceous restrictive layer's distribution across the Northeast Black Soil Region. Results showed a total distribution area of 8137 km2, concentrated in Jixi, Jilin, Tieling, and Hulunbuir cities. Key physicochemical parameters include depth (28.80–65.30 cm), thickness (51.52–92.35 cm), silica neoformation abundance (18.50–29.62%), and silica neoformation density (302.98–629.86 g/dm$^3$).

To address characteristic patterns, 30 representative soil profiles were analyzed across diverse climatic zones, topographic positions, and geological periods. Statistical analyses revealed distinct properties including low organic carbon content, moderate total nitrogen and phosphorus levels, elevated available phosphorus, high bulk density, and weakly acidic pH. Particle size distribution showed silt dominance, while geochemical signatures exhibited elevated $SiO_2$ proportions, moderate Fe/Al ratios, high silicate activity factor (Saf), and intermediate eluviation indices.

The formation mechanism was reconstructed through multidisciplinary evidence, revealing dual regulatory mechanisms: in terrace-hilly landscapes, groundwater dynamics interact with biological cycling to drive silica accumulation; in mountainous regions, biogeochemical processes dominate, characterized by plant-mediated silica enrichment and detrital recycling.

This research provides critical insights into the genesis of siliceous restrictive layers, offering robust scientific foundations for: (1) targeted soil management strategies to enhance black soil productivity, (2) refined classification criteria for Chinese Soil Taxonomy, and (3) sustainable agricultural development in vulnerable black soil ecosystems. The integrated methodology establishes a template for investigating analogous soil horizon phenomena globally.

**Acknowledgments**

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# Revisiting krotovina formation using luminescence dating - a case study from NE China

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**ABSTRACT**

Krotovinas, the infilled burrows created by small mammals through bioturbation, represent a distinct pedogenic process and provide valuable records of soil and landscape history. Traditionally, macro- and micromorphological features are analyzed to investigate the origin of burrow fills, and ages are often estimated using 14C dating. However, in some environments, morphological features can be misleading and material for 14C dating is insufficient. This study explores the potential of luminescence techniques to address these issues. We studied a Chernozem profile with typical krotovinas, forming from fluvial sediment in northeast China. Three krotovinas of different depths and colors (two black and one yellow) were sampled, along with their respective supposedly undisturbed counterparts from the surrounding soil. We conducted single-grain (SG) luminescence dating of the K-feldspar fraction and multigrain (MG) luminescence dating of both quartz and K-feldspar fractions. Significant differences in luminescence ages between samples inside and outside the krotovinas at both MG and SG levels suggest the presence of vertical bioturbation. Comparisons of SG distributions among samples indicate that the yellow krotovina at ca.70 cm was the result of upward transportation from a lower layer and was formed after the end of the Last Glacial Maximum. The two black krotovinas at ca. 80 and 160 cm are genetically linked, and probably formed in a single, rapid, simultaneous filling event occurring no earlier than 2.7 ka. This study highlights the unique role of luminescence dating in elucidating formation processes of krotovinas and the soils in which they are found.

**Keywords:** krotovina, bioturbation, single-grain luminescence, Chernozem

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# The basalt – laterite sequences in the Leizhou Peninsula, South China: Indicating multiple alternations between volcanic eruption and laterite formation in the tropical region since the Middle Pleistocene

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**ABSTRACT**

In the Leizhou Peninsula - northern Hainan Island region, South China, there were at least six large-scale volcanic eruptions in the Quaternary period. After a volcanic eruption each time, the surface was covered by basalitic rock. Under the tropical climate, the basalt was intensely weathered and finally developed into laterite. When the next volcano erupted, however, the laterite formed on the surface would be covered by a new layer of basalt. In this way, a unique sequence of multiple cycles of basalt alternating laterite was formed.

Two sections composed of modern laterite—basalt—buried paleo-laterite were collected in the Yingfeng Ridge and Qujie Town in Xuwen County of the Leizhou Peninsula, Guangdong Province, South China. The physical and chemical characteristics of each layer of the sections were studied. There were significant differences in various characteristics between the modern laterite and buried paleo-laterite formed in the Middle Pleistocene. The colors, pH, magnetic susceptibility (χlf), free iron (Fed), and total iron (Fet) of the modern laterite are 10YR4/4, 4.69, 1500×10−8 m3 kg−1, 101.2 mg g-1 and 211.1 mg g-1 on average; and these of the buried paleo-laterite are 10R4/8, 4.53, 226×10−8 m3 kg−1,155.5 mg g-1 and 218.6 mg g-1 on average, respectively. The molecular ratios of SiO2/Al2O3, SiO2/(Al2O3+Fe2O3) and (CaO+MgO+K2O+Na2O)/Al2O3, and Fed/Fet of the modern laterite are 2.07, 1.41, 0.017 and 0.479 on average; and these of the paleo-laterite are 2.06, 1.39, 0.012 and 0.711 on average, respectively.

The curves of trace element distribution of the modern laterite, basalt, and paleo-laterite of the sections are completely consistent. This indicates that the laterites are derived from the same source of basaltic rock. Compared with the modern laterite, the paleo-laterite formed in the Middle Pleistocene is redder in color hue and significantly higher in pedogenic Fe oxides, indicating stronger chemical weathering. χlf value of the paleo-laterite is lower, probably due to the effect of high-temperature demagnetization when it was covered by hot lava.

The basalt-laterite sequence in the Leizhou Peninsula perfectly reserves the paleo-laterite in the Middle Pleistocene, reflecting that the climate in the low-latitude tropical region was more humid and warmer in the Middle Pleistocene, when the weathering and pedogenic effects on the surface were much stronger; by the Late Pleistocene, the climate turned cooler and the development of laterite on the surface was weakened. This also suggests that there have been significant climate changes even in tropical regions since the Middle Pleistocene.

# The Final Stage Of Loess Accumulation In The Glacial Region Of The Last Glaciation And Its Reflection In The Properties Of Modern Soils: A Case Study Of Northwestern Russia.

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**ABSTRACT**

In the region of the last (Valdai, Ostashkovo) glaciation in the northwest of the Russian Plain, Holocene soils form mainly on glacial deposits. During large-scale soil mapping of fallow lands in the Leningrad Region in 2022–2024, we identified soils with silty, carbonate-free, boulderless parent materials atypical for the region. Based on morphological analysis and particle-size distribution, they are similar to loess-like loams (loessoids) of the periglacial zone.

Said layers usually form a thin upper mantle (up to 0.6 m) overlying till or glaciolacustrine clays. In other cases, they can be encountered as a weakly differentiated stratum (visible thickness up to 1.5 m). At one of the study sites (former "Volna" state farm), a series of catena profiles showed that a homogeneous silty stratum (possibly cover loam) has a consistent thickness over 100 cm and lateral extent along the slope. It overlays sorted, silty loamy sands, sometimes with sand interlayers. Morphological variation in soil profiles is weakly expressed.

The lack of correlation with specific landforms may be explained by local supply of silty material via aeolian transport from the zone of a pulsating retreating glacier during the Late Glacial. Such deposits can be considered a niveo-aeolian variant of loessoids.

Recent studies in Fennoscandia indicate that aeolian activity intensified during glacier retreat (14.4–13.8 ka BP). Recent data from Sweden (Gothenburg area) also confirm the presence of a thin (0.15–0.80 m) loess mantle ("flygmo") deposited about 14 ka BP.

In conclusion, the study confirms the presence of Late Glacial loess-like mantles in the northwest Russian Plain, attributed to local niveo-aeolian processes during glacier retreat. This finding aligns with the regional paleogeographic model of Fennoscandia and highlights the significant role of aeolian activity in the area's postglacial sedimentogenesis. Further research, including absolute dating, is required for detailed chronological and genetic analysis.

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# Palaeobotanical records from soil infill of rodent burrows reveal Mid- to Late-Holocene environmental dynamics: A case study from the central chernozem region of Russia

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**ABSTRACT**

The forest-steppe is among the most complex and climatically sensitive ecosystems of the Northern Hemisphere, where closed-canopy forests and open steppe communities coexist across the Eurasian forest-steppe zone extending from eastern Europe to China and covering ~2.9 million km². During the Holocene, the southern limit of forest distribution fluctuated repeatedly, retreating northwards during more arid phases and advancing southwards under more humid conditions. However, the spatio-temporal patterns and drivers of these shifts remain poorly understood.

Here we present a novel, original palaeopedological methodology that uses infilled burrows of fossorial mammals ("krotovinas") preserved in Chernozems as a widely available, soil-based palaeoarchive in arid ecosystems. Using a multi-proxy approach integrating soil properties with pollen analyses (incl. non-pollen palynomorphs), and AMS radiocarbon dating, we demonstrate that krotovina infills provide a robust and scalable archive for reconstructing Holocene vegetation and moisture dynamics across the forest-steppe and steppe zones.

We investigated seven sites in Belgorod Oblast (East European Plain), where Chernozem profiles contain abundant krotovinas attributed to the greater blind mole-rat (Spalax microphthalmus). We sampled 27 krotovina infills and collected 8 surface References samples. Soil organic carbon (SOC) was measured for all samples, and the chronology was established using AMS radiocarbon dating of the SOC fraction from 14 infills. Pollen analysis, supplemented by identification of non-pollen palynomorphs, was conducted for the entire dataset. The studied krotovina infills span ~8.4–2.3 ka cal BP, and stratigraphic and pedological patterns support this temporal ordering: older infills occur deeper in the profiles and exhibit lower SOC, paler colours, and more diffuse boundaries. All infills contained pollen in sufficient quantities and with adequate preservation to enable reliable vegetation reconstruction. Surface samples reflect disturbed meadow-steppe vegetation, whereas krotovina spectra span a broad range from relatively forested to dry steppe communities. Ordination of krotovina spectra along SOC and age gradients indicates major shifts in vegetation cover, from Artemisia-dominated xerophytic steppe to wetter, warm-climate meadow-steppe with increasing forest cover. From ~4900 cal yr BP onwards, spectra increasingly reflect anthropogenic landscape transformation, with clear signals of pastoralism and vegetation disturbances.

Overall, krotovina infills preserved in Chernozems provide a palaeoarchive that fills the gap between wetland records and limited palaeosols. This methodology has strong potential for reconstructing vegetation and land-use dynamics across the Eurasian forest-steppes and the North American prairies.

**Acknowledgments**

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# Climate-driven silicate weathering and biogeochemical coupling in black soils

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**ABSTRACT**

The black soil region of Northeast China has revealed widespread silica-clay composite layers that constrained crop root, yet their origin—chemical weathering versus biological enrichment remains debated. Here, a sequential chemical extraction method and biogeochemical coupling analysis were applied to demonstrate that the total Si pool in black soil consists predominantly of Si (residual silicon ($Si_{res}$): 96.02%−97.34%), with non-crystalline silicon ($Si_{noncry}$) accounting for 2.66%−3.98%. Silica neoformation accumulation layers demonstrated marked enrichment in $Si_{res}$. Overall, soil pH, organic carbon content, and bulk density regulated the vertical differentiation of Si fractions by influencing silicate dissolution-precipitation dynamics and cementation processes. A quantitative model of Si biogeochemical ratio was proposed and used to quantify interaction intensity between biological and chemical processes. Holocene climatic cycles drove silicate migration and transformation, with chemical weathering dominating during glacial periods and biological processes intensifying during interglacial phases, revealing co-dominant roles of biological and chemical processes in forming silica neoformation accumulation layers. This study clarifies that climate-driven biogeochemical coupling shapes silica neoformation accumulation layers in black soils, providing a theoretical basis for understanding pedogenesis.

**Acknowledgments**

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# Radiocarbon dating: new approaches in soils and paleosols – are these new opportunities or problems?

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**ABSTRACT**

The radiocarbon method is actively used in soil science and paleopedology to determine soil age, carbon exchange rates in the soil-atmosphere system, organic matter dynamics, and geochronological reconstructions. The first data on the radiocarbon age of soil organic matter (SOM) were published in 1959 by R. Simonson, who determined the age of meadow soils in North Dakota to be approximately 1,300 years before present (BP). Over the past nearly 70 years, radiocarbon dating has become a routine procedure in soil science, especially in paleosol science. A large array of $^{14}C$ data for soils from different regions has been accumulated, and an International Soil Radiocarbon Database, ISRaD, has been established (http://www.soilradiocarbon.org).

The development of accelerator mass spectrometry (AMS) has enabled soil scientists to date individual SOM fractions, biomarkers isolated from buried soils, date soil carbonate formations layer by layer, and date paleosols with low carbon content. However, as in previous years, the interpretation of data obtained for soils is not always unambiguous. When interpreting the data, it is important to understand the source of carbon in the dated sample, whether the dated pool is homogeneous or heterogeneous, and whether the system was open, open-closed (which applies to most dated soils), or closed. In most ecosystems, SOM is best viewed as an open system where new carbon is constantly being added via photosynthesis and organism death, while older C is constantly removed by microbial decomposition. These processes operate concurrently on the bulk

SOM pool over a range of timescales from minutes to millennia. The exchange rate of C from organic soil pools is difficult to quantify due to this wide range of timescales, and $^{14}C$ provides one of the few tools for determining in situ soil C dynamics in both disturbed and undisturbed ecosystems.

Depending on the research objectives, different approaches are chosen to isolate soil fractions for dating. It should be acknowledged that at present there is no single approach to dating soil organic matter or a universal dating fraction that would be effective in all soil studies. To interpret the age of soils based on $^{14}C$ data, it would probably be necessary to fractionate the sample into components that differ in their mechanisms of organic matter stabilization.

Despite the numerous new analytical possibilities in $^{14}C$ dating soil organic and inorganic carbon that are opening up to us, we must first and foremost adopt the perspective of a soil scientist and carefully design our research before simply obtaining a radiocarbon data.

# Soil-Permafrost Complexes of the Russian North-East Arctic Accumulative Sea Coasts: Structure, Properties, Diagnostics, Ecological Functions

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**ABSTRACT**

The soils and the upper permafrost on the coasts of Arctic seas remain poorly studied due to their hard accessibility but obviously demand thorough studying in the nearest future. The large length of the coastline, the diversity of coastal geomorphic features, landscapes, sediments, the character of tidal and surge phenomena, and the salinity of the sea determine the formation of a wide range of permafrost-affected soils. The morphology of soils on the Arctic coasts are complicated by the severity of the climate, cryogenic processes, and specific biota. A significant part of the coasts here belongs to the accumulative coasts with very gentle slopes (e.g. in the Russian North-East Arctic region). This leads to the penetration of surge water to the inland for tens of kilometers; seawater feeds numerous small thermokarst lakes, flooded swampy meadows, and cryogenic polygons, which also affects soil and permafrost formation here.

Our study suggests distinguishing three major areas of sea-soil-permafrost interaction on the accumulative sea coasts.

*Weakly developed permafrost-affected marsh soils* are characterized by the weak development of the sandy-loamy profiles by postlithogenic pedogenesis, close occurrence of the permafrost aquiclude, and watering of the profiles. The saturation of soils with water during tides and surges prevents the active entry of fresh portions of salts into the soils and their redistribution within the soil profiles. Often the maximum content of soluble salts in the profile is shifted to the suprapermafrost horizon. The material of these horizons may remain in a thawed state (without ice) at subzero (up to –1…–2.5°C) temperatures. The closest WRB analogue here is most probably *Tidalic Arenosols gelic (loamic)*.

*Permafrost-affected marsh soils* of Arctic coasts display quite definite relationships between their morphology and properties and the distance from the sea, the development of cryogenic polygonal microtopography, waterlogging of the profiles, and vegetation. Peat horizons bear signs of siltation, and deeper mineral layers are differentiated into genetic horizons. Their properties and structure retain features inherited from previous, more active stages of synlithogenic soil formation, which are superimposed by the influence of modern postlithogenic soil formation. The closest WRB analogue here is *Tidalic Gleysols gelic histic*.

*Maritime permafrost-affected soils* have the morphology of the zonal soils (mainly Cryosols and Gleysols). The influence of the sea on them is manifested by the presence of some features that do not develop into separate genetic horizons and is associated with the aerial transport and deposition of salts and plant detritus from tidal flats and tidal marshes and an increased soil moistening owing to the proximity of the sea. The closest WRB analogue here is *(Proto-)Salic Cryosols/Gleysols chloridic/sulphatic*.

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# Suggestions for Classifying Soils of the Retrogressive Thaw Slumps Impact Zone in Future Russian and International Soil Taxonomies

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**ABSTRACT**

Thermodenudation is a process of permafrost sediments destruction and redistribution. It activates due to climate warming and humidization, and initiates as well by some other natural and technogenic factors. Retrogressive Thaw Slumps (RTS) are widely distributed across plain and mountainous permafrost zone. Their properties depend on local conditions. Common impacts of all RTS are dramatic shifts in ecosystem structures (including soil cover and upper permafrost) (Nesterova et al., 2024).

There is a lack of research on soil dynamics under RTS impact. No standardized soil profile descriptions, no soil diagnostic horizons, and no approaches to classification of such soils exist at the moment. Basing on personal experience of permafrost-affected soils field studies, we began filling this gap.

The principal scheme of synlithogenic soils development under RTS impact includes 4 stages: 1) accumulation of organo-mineral material; 2) stabilization and initial drainage of soil surface (initial algae-moss-lichen vegetation); 3) full soil drainage (graminoid-grass vegetation); 4) transition to postlithogenic development (moss-shrub tundra). These stages could change each other consequently or repeat cyclically in case of thermodenudation reactivation. The diagnostic horizon of such soils is the "thermodenudationally-accumulated material" (RAtd) – mixed, water-saturated (incl. thixothropy) organo-mineral horizon that could also include fragments of soil organic matter, Fe, Mn and S compounds' new formations etc. Its structure, texture, physico-chemical and biological properties vary depending on the parent material properties. We suggest introducing the new sub-type – *"Thermodenudationally-accumulated stratozems"*, – into the further versions of the Russian Soil Taxonomy within the stem of synlithogenic soils, stratozems order. If the RAtd thickness do not exceed 40 cm, the sub-type *"Thermodenudationally-stratified"* should be used for soils from other stems and orders. In implement to the WRB we suggest changing the list of diagnostic properties for the *"solimovic"* qualifier, and to make it possible to use it for slumps formed by sediments of marine-, lacustrine-, fluvial- etc. origin (incl. perennially frozen).

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# Spatiotemporal Variations of Soil Hydrothermal Processes and Their Association with Mattic Layer Rupture in Alpine Soils on the Qinghai-Tibetan Plateau

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**ABSTRACT**

The mattic layer (ML), a dense root-soil matrix formed predominantly by Kobresia sedges, constitutes a keystone subsystem governing ecosystem functioning across 2.5 million km² of the Qinghai-Tibetan Plateau. However, the ML rupture has emerged as a widespread structural failure threatening this vital ecological barrier. Recent studies suggest that ML rupture is driven by synergistic anthropogenic and natural factors, yet the underlying mechanisms, particularly the role of soil thermal-hydrological processes, remain poorly understood. Therefore, this study explored relationships between soil thermal-hydrological dynamics and ML rupture distribution using multi-scale analysis method in a typical ML rupture area on the QTP. A total of 10 in-situ monitoring instruments were set up across different topographic positions and vegetation cover types, and soil temperature and moisture data from 0-50 cm depth with 10 cm interval were hourly recorded, respectively. The spatial-temporal variation of soil thermal-hydrological conditions were mapped using 13 related environmental variables that derived from high-resolution UAV measurements. The spatial distribution of ML ruptures was overlaid with soil thermal-hydrological maps in pixel level. A total of eight core landscape metrics were employed to quantify ML rupture severity and its relationship with thermal-hydrological conditions. Statistical analyses combined Welch's t-test and Cohen's d effect size revealed significant differences in soil temperature and moisture conditions between ruptured and intact ML areas, with the most pronounced disparities observed during critical months including January, April, and September. Results also showed that ML rupture is primarily driven by intense soil freeze-thaw alternation. Freeze-thaw intensity decreased significantly with depth, with surface layers exhibiting the most active freeze-thaw dynamics. Spearman correlation analysis revealed that freeze-thaw cycling frequency exhibited the strongest association with rupture severity (r=0.66 with largest patch index, r=0.76 with nearest neighbor distance). These findings provide quantitative evidence supporting the hypothesis that ML rupture occurrence and aggravation was correlate to the thermal-hydrological spatial and temporal variations, especially the area with intense and frequent soil freeze-thaw alternation are more fragile. The results can be used to develop space-time precision conservation strategies in degraded alpine pasture ecosystems.

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# Structural Features of Soils and Upper Permafrost of Eastern Chukotka Coastal Plains

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**ABSTRACT**

Soils and upper permafrost horizons are complex and dynamic systems in modern climate change especially in such remote permafrost-affected areas as Eastern Chukotka, where climate-derived permafrost dynamics are obvious. Here we represent one of the first ever soil cover descriptions at Eastern Chukotka coastal plains, located in continuous permafrost zone. We also report about key features of the spatial distribution of the upper permafrost horizons and their relationships with soils. This research took place in August 2025 along the transect through different geomorphological levels – fluvio-glacial plain, marine and glacial-marine terrace, marine terrace and alluvial terrace. The most common soils are Turbic Oxyaquic Histic Coarsic Cryosols (Clayic/Loamic, Thixotropic) and Oxygleyic Histic Gleysols (Clayic, Loamic, Skeletic). The main feature of interaction of permafrost-affected soils and underlaying permafrost layers is an evidence of the ice-rich layers, also known as transient and intermediate layers. They have specific cryogenic structures (suspended and reticulate) with visible ice exceeding 50%. For the reason these layers protect permafrost from accelerating climate warming (Shur et al., 2005). This layer thickness was 53–165 cm depending on geomorphological position and sediment's texture. Transient and intermediate layers include some visible pedogenic features – Fe and Mn oxides and coarse organic matter fragments. These features were transported through soil profiles and buried in transient/intermediate layers via processes of cryoturbation and vertical migration after chemical/physical leaching.

**Acknowledgments**

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# Wildfires accelerate permafrost area loss via reducing soil organic matter

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**ABSTRACT**

The stability of permafrost and its vast carbon stock is regulated by the insulating properties of soil organic carbon (SOC). However, intensifying wildfires across the Arctic and boreal regions are removing the protective soil organic layer, which may trigger a powerful feedback that accelerates thaw, yet the pan-Arctic scale of this threat remains unknown. Here, we combine an empirical model of permafrost probability, constrained by air temperature and SOC, with a pan-Arctic synthesis of SOC combustion and post-fire SOC recover rate, and projections of future climate and fire activities. We find that under a low-emission scenario (SSP1-2.6), fire-induced SOC loss, considering both combustion and post-fire recovery, reaches 20 ± 4 Pg C by 2100, which drives an additional permafrost loss of 3.6 ± 0.8 million hectares. This fire-driven permafrost loss is less pronounced under high-emission scenarios, where rapid atmospheric warming is the predominant driver. Under SSP1-2.6, every 1 km² of increased burned area is projected to cause a 0.25 km² of permafrost loss, highlighting the process's efficiency. Our results reveal a critical fire-SOC-permafrost feedback that disproportionately undermines permafrost stability in scenarios that achieve moderate climate mitigation. Without considering the effects of wildfire on soil thermal properties, current Earth system models likely underestimate future permafrost degradation.

# The $CO_2$ and $CH_4$ fluxes from the epiphytic lichen Evernia mesomorpha collected in boreal forest underlain by cryosols

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## ABSTRACT

The study examined greenhouse gas ($CO_2$ and $CH_4$) fluxes from the surface of the epiphytic lichen (EL) Evernia mesomorpha, which is typical for larch forests that are underlain by permafrost. The research was conducted near the Tura Experimental Station, located in the Tura settlement within the Krasnoyarsk region of Russia. The site is located in the northern part of Middle Siberia, in the middle reaches of the Nizhnyaya Tunguska River (64°18′ N, 100°11′ E). According to Russia's soil-geographic classification, the area is part of the Central Siberian province, which features permafrost-affected taiga soils predominantly consisting of cryozems. The development of these soils is influenced by the region's cold, humid climate and the presence of shallow permafrost, which thaws to a depth of approximately 70 cm by the end of summer. The larch stands in this area are relatively sparse, allowing solar radiation and winds to impact the surface [2, 3].

ELs are poikilohydric organisms that activate defense mechanisms to safeguard their tissues and metabolic processes from dehydration-induced damage. Unlike higher plants, lichens lack the ability to regulate the moisture entering or evaporating through their cells via stomata. As a result, they experience frequent cycles of wetting and drying (poikilohydry), which are influenced by the availability of dew, rain, snow, or high air humidity [1]. This capacity of ELs is particularly intriguing when assessing the effects of varying hydration levels in lichen thalli on greenhouse gas (GHG) fluxes, especially $CO_2$ and $CH_4$.

In this study, we examined the impact of varying water content in the thallus of E. mesomorpha on greenhouse gas ($CO_2$, $CH_4$) fluxes during an incubation experiment. Samples of E. mesomorpha were collected in June from the branches of larch trees (Larix gmelinii). The samples were moistened with artificial rainwater to achieve thallus moisture levels of 50%, 100%, 200%, and 400%, and then incubated in triplicate within glass flasks under light for 3 days. Gas samples were collected daily through a gas-tight septum at both the beginning and end of a 2-hour measurement period and analyzed immediately for $CO_2$ and $CH_4$ content using a Picarro 2201-i.

It has been demonstrated that the moisture content of the EL thallus influences both the magnitude and direction of GHG fluxes from its surface. Specifically, the E. mesomorpha thallus increases carbon dioxide ($CO_2$) emissions when exposed to excess moisture, while a decrease in thallus moisture leads to increased methane ($CH_4$) production and $CO_2$ photoassimilation. Furthermore, the branch's exposure (southwest or northeast) affects the EL surface's GHG flux variability.

**Acknowledgments**
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# Greenhouse gas fluxes by the epiphytic lichen Bryoria in response to projected moisture increase in boreal forests underlain by thawed permafrost soils

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**ABSTRACT**

Currently, much research focuses on the carbon (C) cycle and temperature-dependent processes in high latitudes that cause climate change, while there is insufficient information about the role of lichens, including epiphytes (EL), in the C balance of such ecosystems, especially in the continuous permafrost zone of Middle Siberia. Therefore, the aim of this study was to assess the actual and potential fluxes of carbon dioxide ($CO_2$) and methane ($CH_4$) in one of the most common lichen species, *Bryoria simplicior* (Vain.) Brodo et D. Hawksw., inhabiting larch trees (*Larix gmelinii* (Rupr.) Rupr.) in the continuous permafrost zone of Central Siberia (Tura settlement, Krasnoyarsk region, Russia). Seasonal studies (from mid-June to August 23, 2025) of greenhouse gas (GHG) fluxes from *Bryoria* transplants showed $CO_2$ fluxes ranging from -627 mg $CO^2$ $m^{-2}$ $h^{-1}$ ($CO_2$ photoassimilation) to 1011 mg $CO_2$ $m^{-2}$ $h^{-1}$ (predominantly $CO_2$ release). Regarding methane, its consumption by *Bryoria* transplants was mainly detected during the growing season. Although methane release cases were observed at high levels of lichen thallus hydration (over 600%) due to prolonged rainfall (e.g., DOY 177 and 179). The incubation experiment aimed to assess potential fluxes of GHGs under polar day conditions. To simulate these conditions, we used a photoperiod of 12 hours of light at +20°C and illumination (PAR=100-200 µmol photons $m^{-2}$ $s^{-1}$) and 12 hours at 10°C and supplemental lighting at PAR=10 µmol photons $m^{-2}$ $s^{-1}$. Thallus water content was 50, 100, and 200%. Incubation in light conditions revealed the influence of the tree stem exposure (northern or eastern) where the ELs were growing on the $CO_2$ flux rate (up to 136 µg C-$CO_2$ $g^{-1}$ $h^{-1}$) only at a thallus water content of 200%. During the 3-day aerobic incubation of *Bryoria* in light conditions, methane emissions were observed up to 2.06 ng C-$CH_4$ $g^{-1}$ $h^{-1}$ at all levels of thallus water content. It is expected that new data on ELs GHG fluxes in the context of varying thallus moisture due to changes in precipitation patterns will allow for a review of overall GHG flux estimates in forest ecosystems, thereby improving our understanding of current processes and future projections.

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# Enzymatic activity in podzols of the north of Yamalo-Nenets Autonomous Okrug

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**ABSTRACT**

The uniqueness of the cryolithozone's soil cover and ecosystem is determined by their properties formed in permafrost zones and exposure to harsh climatic conditions for at least 9 months. Here, soil freezing processes have a significant impact on soil formation, manifesting themselves in physical fragmentation during freeze-thaw cycles, coagulation, and crystallization. The influence of these processes on the biological activity of cryolithozone soils is enormous. The functioning of microbial communities in the north is influenced by temperatures, low pH values, and the specific composition of organic residues entering the soil. Of particular interest in this region is the activity of soil enzymes, which perform a variety of functions in the soil: decomposition of mineral and organic matter; maintenance of soil homeostasis; participation in humus biogenesis and soil metabolism under unfavorable conditions for microorganisms. The aim of our study is to characterize the biological activity of podzols in the south of the Yamal Peninsula.

The study subjects were podzols collected in the south of the peninsula—raw-humus podzols and turbated peat podzols, represented by natural variants and anthropogenically transformed "analogues." Soil samples were collected in the summer of 2023, both within the Arctic Circle, north of Novy Urengoy, and in the city itself.

Most of the territory is occupied by tundra with characteristic cryogenic landforms: frost mounds (pingos), thermokarst funnels, and medallion spots. The parent rocks are sandy and lacustrine-alluvial deposits with low iron content.

In all soils, the activity of catalase and invertase decreases with depth, which is associated with a decrease in water-soluble organic carbon and labile humic substances, which are a substrate for soil microorganisms. Catalase and invertase enzyme activity is characterized as "very poor" and "poor" in all horizons of the studied soils. The only exceptions are two horizons: the peat horizon of the gley peat-podzol and the Oao horizon of the raw-humus podzol.

Maximum urease activity is determined in the E horizons of the abrazems. In the gley peat-podzol, maximum urease activity is confined to the peat horizon. Dehydrogenase activity was diagnosed only in three horizons: T2 of gley peat-podzol, O of coarse-humus podzol, and E horizon of alfehumus abrazem.

# Landscape Conditions of Soil Formation in Drained Lake Basins of the Russian European North

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**ABSTRACT**

A study of the spatial differentiation of landscapes and soil cover in the drained basins of the Bolshezemelskaya Tundra has revealed their significant diversity. The investigated basins are divided into two main groups: those with peat soils and those with mineral ones. Peat basins are differentiated by their geocryological conditions and soil cover composition. Among them, drained lake basins with permafrost-affected and seasonally frozen peat soils are distinguished. Mineral basins are divided according to their degree of drainage/wetland status and the soil composition of the coastal sites of lake terraces. Among the mineral ones, waterlogged and drained basins with peat-covered shores, as well as waterlogged basins with mineral shores, are identified. Basins with peat soils are confined to areas of permafrost peatlands. The presence of mineral soils in the basins is determined by a number of factors: a significant proportion of mineral soils in the coastal terraces and their low degree of peat formation; good current drainage and complex, rugged relief of the basin floor; a high shoreline sinuosity coefficient. Favorable conditions for waterlogging often develop in basins with mineral soils. The water saturation of the Histic soils in these basins inhibits the formation of near-surface permafrost. The study of the facies and soil diversity of the lake-bog landscapes led to the derivation of landscape-soil formulas. In a comparative analysis of the landscape-soil conditions in the basins and the surrounding areas, these formulas form "equations." The use of landscape-soil "equations" makes it possible to effectively analyze the landscape conditions and soil cover of the drained basins with their subsequent differentiation. Thus, the formation of various subgroups of drained basins is due to a complex of factors determined by the composition of the coastal terrace sites, the morphometric characteristics of the lake basins, and their landscape position. The complex spatial changes of these factors form a landscape-soil continuum, which, using the proposed «equations» describes a gradual transition from basins with peat soils to those with mineral soils.

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# Features of Soil Formation in Khasyreys (Tundra Thermokarst Depressions)

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**ABSTRACT**

Tundra thermokarst depressions (Khasyreys) – former lakes – are widespread across the lowland tundra. Khasyreys generate as a result of permafrost degradation, where ground ice melts, the soil subsides, and a closed depression forms in place of the lake. This process is dynamic and has become increasingly active due to climate change. Furthermore, as part of Soviet programs to create meadows in the tundra as a forage base for agriculture, thermokarst lakes were artificially drained.

Two drained thermokarst lake depressions in the Bolshezemelskaya Tundra (Piatomboy-Glad' locality) were selected to study the specific features of the structure, properties, and temperature regimes of the soils. These khasyreys differ in their genesis (natural and artificial drainage) and the lithology of their bottom sediments (mineral with clays and sands, and organo-mineral, respectively).

The characteristics of the soil cover and soil properties are determined by the composition of the parent materials. In Khasyrey 1 (naturally drained with mineral sediments), soils typical for the region formed: Histic Reductaquic Cryosols and Gleyic Arenosols (Gelic). In Khasyrey 2 (artificially drained, with organo-mineral sediments), soils unique to the tundra occured: Sapric Cryic Histosols (Mineralic) and Gleyic Fluvisols (Arenic, Folic). The presence of humus-stratified mineral horizons is explained by the accumulation of silty material in the peat-mineral deposits during the period they were submerged (until 1979). The peat horizons are similar to those in Fibric Histosols on peat plateasus in tundra.

The physicochemical properties of the soils correlate with their genesis. All soils have an acidic reaction and a low/medium base saturation. The soils of Khasyrey 2, including the organogenic Sapric Cryic Histosols (Mineralic), are characterized by high ash content (40-50%), which is associated with siltation during the lake's existence. The carbon content is highest in the Sapric Cryic Histosols (Mineralic) (20-30%); however, the C/N ratio (16-19) indicates a relatively low enrichment of carbon with nitrogen.

The soil temperature regimes in the basins also differ significantly. The Gleyic Arenosols (Gelic) are characterized by deep seasonal freezing, significant summer warming, and intense winter cooling (a cold mid-depth permafrost profile). The Sapric Cryic Histosols (Mineralic) have a milder temperature regime with a shallow active layer, but with permafrost close to the surface (a cool shallow permafrost profile). The thick peat layer acts as a thermal insulator.

Cryogenic processes play a key role. The permafrost-affected soils in both basins belong to different types: in Khasyrey 1, they are "ecosystem-modified" (formed in a cold climate and preserved due to a thin organogenic horizon); in Khasyrey 2, they are "ecosystem-protected" (generated under colder conditions and preserved due to a thick, thermally insulating peat-mineral layer).

Thus, the structure, properties, and thermal regime of soils in drained lake depressions (Khasyreys) are determined by the lithology of the bottom sediments and the history of landscape evolution. The presence of organogenic horizons of varying thickness is a key factor providing protection for the permafrost from thawing.

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# Freeze-Thaw-Driven Soil Moisture Return Significantly Contributes to Spring Phenology on the Warming Qinghai-Tibet Plateau

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**ABSTRACT**

In the context of climate change, the direct impact of temperature and precipitation on the start of the growing season (SOS) and carbon uptake on the Qinghai-Tibet Plateau (QTP) is well documented, yet the potential influence on spring soil moisture return (SMR) dynamics from freeze to thaw remains insufficiently understood. Here, we integrated multi-source data from 32 observing sites over QTP (2003-2024) and proposed a novel framework to quantify the removal degree of evapotranspiration moisture limitation (REML) by hydrological processes. The REML effect induced by freeze-thaw-driven SMR and spring precipitation was decoupled and quantified as $E_{SMR}$ and $E_{prec}$, respectively. Across the study sites, $E_{SMR}$ contributed 20.7% ± 2.1% (mean ± SD) of the SOS advance since 2003, surpassing the effects of $E_{prec}$ and air temperature, underscoring the role of pre-freezing moisture return in advancing SOS in the following spring. At sites with active layer thickness (ALT) exceeding 2.2 m, the $E_{SMR}$ exhibited ~24% higher sensitivity to surface soil moisture compared to sites with thinner ALT. We found that, compared to the direct impact of spring precipitation, the augmentation of pre-freezing surface soil moisture by prior summer-autumn precipitation and the overwintering SMR more strongly advance the following year's SOS ($p < 0.01$). As ALT deepens, the influence of soil moisture dynamics in the middle and lower active layers, associated with permafrost degradation, may gradually weaken in regulating SOS. Overall, our results provide a new insight into the underlying mechanisms of the nonlinear regulation of SOS by multiple hydrological processes over permafrost regions.

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# Transformation of Soil Organic Matter in Agricultural Soils in Subarctic Climatic Conditions

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**ABSTRACT**

Investigated post-agrogenic transformation of Plaggic Podzols in the Yamal region (Western Siberia, Russia) using a chronosequence approach (0–25 years of abandonment) and a long-term fertilized References site (>90 years of management). Elemental (CHN-O) analysis, solid-state $^{13}C$ NMR spectroscopy, PXRD, and multivariate statistics were applied to assess soil organic matter (SOM) dynamics under harsh climatic conditions (mean annual temperature −5.1 °C, <70-day growing season). Results show an initial increase in soil organic carbon (SOC) during early abandonment (5–10 years: 3.75–4.03%), followed by significant depletion after 25 years (2.15–2.27%). This decline is attributed to limited organo-mineral stabilization in quartz-dominated, sandy soils with low clay content (5.3–12.4%) and negligible reactive mineral phases. Continuous organic fertilization at the Yamal Agricultural Station sustained higher SOC (3.58–3.83%), balanced C:N ratios (19–20), and preserved labile alkyl-C (39.61%), demonstrating the critical role of external organic inputs in compensating for poor mineralogical protection. $^{13}C$ NMR revealed progressive molecular shifts: active fields were rich in alkyl-C (40.88%), while abandoned soils showed enrichment in O-alkyl-C (21.6%) and lignin-derived aryl-C (15.88%), indicating microbial processing and humification. However, without mineral binding, these recalcitrant compounds remain vulnerable. Freeze–thaw cycles further destabilize SOM by disrupting soil aggregates, a key physical protection mechanism in temperate zones but ineffective here due to cryogenic disturbances and weak organic binding. Principal Component Analysis linked SOC loss to declining nutrient retention (P, K, N), reduced cation exchange capacity (CEC: from 12.3 to 9.5 mEq/100g), and increasing oxidation of SOM (O:C ratio: from 0.68 to 0.83). Despite degradation trends, SOC/clay ratios remained above the 1:13 threshold, suggesting structural integrity has not yet collapsed. Trace metal concentrations were below pollution limits (PLI = 0.63; RI = 46.2), confirming minimal ecological risk. The findings underscore the fragility of SOM in Subarctic agroecosystems and emphasize that sustained organic amendments are essential to maintain soil fertility and carbon stocks under climate and mineralogical constraints.

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# Greenhouse Gas Fluxes from Different Species of Epigeic Lichen Species on Arctic Tundra Cryosols

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**ABSTRACT**

Investigating the contributions of different lichen species to greenhouse gas (GHG) emissions and uptake is crucial for predicting the responses of cryospheric ecosystems to climate change, as epigeic lichens are a key component of ground cover in the Arctic. Furthermore, their role in the GHG balance ($CO_2$ and $CH_4$) remains poorly understood. This study was conducted in July 2025 at two sites in the Arctic tundra, underlain by continuous permafrost, near Dudinka in the Krasnoyarsk region of Russia: one site represented tundra (a shrub-lichen-moss tundra), while the other was a forest-tundra site (a larch open forest with shrub-lichen-moss cover, located on a site affected by fire 30 to 40 years ago), both based on Histic Turbic Cryosols [ 1]. GHG fluxes were measured in situ using a custom-designed transparent chamber connected to a Picarro G4301 gas analyzer. Measurements were taken from pure mono-species mats of dominant lichens (Cladonia spp., Flavocetraria nivalis, Thamnolia vermicularis, Nephroma arcticum, and Alectoria ochroleuca) as well as from bare ground. Testing for the normality of the residuals' distribution and the homogeneity of variances indicated the necessity of employing nonparametric analysis methods. Non-parametric tests, quantile regression, and PCA analysis were utilized to assess the influence of lichen taxon and moisture content and photosynthetically active radiation (PAR) on GHG fluxes.

The tundra site had the highest $CO_2$ flux from bare ground (2.06 µmol $m^{-2}$ $s^{-1}$). The $CO_2$ emission rates varied among the lichen species, with Cladonia (1.46 µmol $m^{-2}$ $s^{-1}$) and Nephroma (1.28 µmol $m^{-2}$ $s^{-1}$) having the highest rates and Flavocetraria (0.248 µmol $m^{-2}$ $s^{-1}$) having the lowest. Statistically significant differences in $CO_2$ fluxes were identified only between bare ground and Flavocetraria ($p<0.001$), indicating photosynthetic activity in the latter. A similar trend was noted at the forest-tundra site: $CO_2$ fluxes from Cladonia (3.04 µmol $m^{-2}$ $s^{-1}$) and Thamnolia (2.72 µmol $m^{-2}$ $s^{-1}$) were significantly higher ($p<0.0001$) than those from Flavocetraria, which showed a flux close to zero or negative (-0.159 µmol $m^{-2}$ $s^{-1}$), thereby confirming its occasional $CO_2$ uptake. All measured plots acted as sinks for atmospheric $CH_4$ at both sites (ranging from -0.0004 to -0.006 µmol $m^{-2}$ $s^{-1}$). On the tundra site, the most substantial $CH_4$ uptake was recorded from Alectoria and Nephroma, significantly exceeding the uptake by bare ground. On the forest-tundra site, $CH_4$ uptake increased in the order Cladonia > Flavocetraria > Thamnolia, with a statistically significant difference between Cladonia and Thamnolia ($p<0.01$). This study demonstrates that GHG fluxes from Histic Turbic Cryosols are strongly controlled by the dominant lichen species, which can reduce $CO_2$ emissions by up to 8 times and increase methane uptake by up to 15 times compared to bare ground. Therefore, predictive models of permafrost-carbon feedback under climate change must account for the projected shifts in lichen communities.

**Acknowledgments**

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# Contrasting Geochemical Signatures of Groundwater and Peatland Waters in Permafrost Bogs of the European Russian Northeast

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**ABSTRACT**

Large mosaic peatland complexes of heaved permafrost peat plateaus, thermokarst fens and thermokarst lakes comprise the dominant landscape components in the European Russian Northeast. Peat plateaus underlain by permafrost cover only about 20% of the Russian European cryolithozone but contain almost 50% of soil organic carbon stocks (SOC), which are considered to be vulnerable to microbial mineralization after permafrost thaw.

Two permafrost bogs were studied in the southern limit of the cryolithozone. At each site, water was sampled from a depth of 10 to 20 cm from the following landscape tracts: peat plateaus, adjacent fens, fens with open water, thermokarst lakes, and streams draining the peatland area. The concentrations of major and trace solutes were measured by methods developed for samples rich in organic matter and low-salinity waters by ICP MS (Agilent Technologies 7500 ce, Santa Clara, CA, USA) and TOC-VCSN (Shimadzu).

A statistical analysis was performed to identify the main distribution patterns of the measured physicochemical parameters (pH, temperature, redox potential - ORP), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), major ions, and trace elements across distinct natural landscape tracts of peatland complexes: peat plateaus (permafrost peat mounds), adjacent (non-permafrost) fens, fens with open water, thermokarst lakes, and streams draining permafrost peatlands.

The most pronounced pattern is a strong negative correlation is observed between pH and ORP – the more acidic the environment, the higher the oxidative potential. A continuum of the landscape tracts is observed from "clean" streams (circumneutral, reducing, influenced by groundwater) to "organic" fens (acidic, oxidizing, with atmospheric nourishment and a strong influence of organic matter). DOC is a key factor controlling the mobility of many elements. Strong positive correlations are observed between DOC and the concentrations of Fe and Al: DOC/Fe and Fe/Al ratios are low in streams and high in fens. DOC forms stable complexes with Fe and Al, leaching them from the peat profile. All REEs show a sharp (orders of magnitude) increase in concentration in fens compared to streams. This is a classic manifestation of organo-complexation. The concentrations of Mn, Zn, As, Cu, Pb are also significantly increase in the acidic, DOC-rich waters of fens. DIC correlates with total mineralization. The highest values of DIC, Ca, Mg, Na, and Sr are found in streams. This indicates feeding by groundwater interacting with bedrock.

Thus, the statistical patterns in the data clearly demonstrate two primary mechanisms governing the chemical composition of natural waters in the region: groundwater geochemistry (determines the composition of streams – circumneutral, reducing, dominated by major ions and bicarbonates) and peatland water geochemistry (determines the composition of fens and lakes – acidic, oxidizing, dominated by organic matter and associated metals and rare earth elements). Samples classified as stream reflect an integral chemical signal from the entire catchment. The stream water is a product of interaction with all the landscape facies and tracts it flows through:

water from fens with high DOC and REE enters the stream; water from peat plateaus also contributes; groundwater interacting with bedrock provides high levels of DIC and major ions. DOC acts as the primary geochemical mobilizer and transporter for a large group of elements in peatland landscapes. A stream serves as an indicator and integrator of the geochemical processes occurring within the multitude of facies in bogs.

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# Environmental controls on soil organic matter composition across a glacial-landscape gradient: A case study of debris-covered glaciers in Gongga Mountain, southwest China

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**ABSTRACT**

Supraglacial debris forms distinct ecological interface on glacier surfaces, representing an early stage of soil development where organic matter accumulation and transformation reflect complex interactions between glacial and terrestrial systems. This study investigated the molecular chemical composition of supraglacial debris organic matter (SDOM) and its environmental controls using pyrolysis-gas chromatography-mass spectrometry on two debris-covered glaciers of Gongga Mountain, southwest China. Despite both glaciers share granite bedrock, they exhibit distinct characteristics in terms of glacier retreat speed, climate, vegetation types, and SDOM content. Pyrolysis products of SDOM identified 95 chemical compounds belonging to 12 molecular classes, which were grouped into eight primary categories: lipids, aromatics, terpenes, N-compounds, carbohydrate-derived, lignin-derived, phenols, and unidentified compounds. Lipids and aromatics were the dominant components, constituting 28.38% and 25.33% of the pyrolysis products, respectively. Spatial variations in SDOM composition were observed between the eastern (Hailuogou Glacier, HG) and western (Dagongba Glacier, DG) slopes, with DG exhibiting higher molecular diversity and abundance. Multiple environmental factors affected SDOM composition, including elemental composition (K and Na), nitrogen and phosphate contents, and debris texture (clay and silt content). The spatial distribution of SDOM characteristics showed systematic variations with elevation and aspect, reflecting the impact of temperature and humidity precipitation on early soil development processes. These findings demonstrate that SDOM composition and initial soil formation in these extreme glacial environments are driven by the combined effects of microbial activities and local environmental factors. Our findings provide new insights into the pedogenic trajectories of high-altitude soil-landscape systems under ongoing environmental change.

**Keywords:** supraglacial debris; organic matter chemistry; Py-GC/MS; debris-covered glaciers; landscape position; Gongga Mountain

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# Minerals and Peroxidases Regulate Soil Carbon Stability in Permafrost

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**ABSTRACT**

Understanding the fate of organic carbon in thawed permafrost is crucial for predicting climate feedback. While minerals and microbial necromass are known to play crucial roles in the long- term stability of organic carbon in subsoils, their exact influence on carbon persistence in permafrost remains uncertain. Our study, combining radiocarbon dating and biomarker analyses, showed that soil organic carbon in Alaskan permafrost had millennial- scale radiocarbon ages and contained only 10%–15% microbial necromass carbon, significantly lower than the global average of ~30%–60%. This ancient carbon exhibited a weak correlation with reactive minerals but a stronger correlation with mineral weathering (reactive iron to total iron ratio). Peroxidase activity displayed a high correlation coefficient ($p < 10^{-6}$) with $\Delta^{14}C$ and $\delta^{13}C$, indicating its strong predictive power for carbon persistence. Further, a positive correlation between peroxidase activity and polysaccharides indicates that increased peroxidase activity may promote the protection of plant residues, potentially by fostering the formation of mineral- organic associations. Tibetan soils contained 4-fold higher microbial residue-derived SOC than Alaskan soils, with fungal necromass three times higher than bacterial necromass, while fungal necromass in Alaskan soils exceeded bacterial necromass by an order of magnitude. In both regions, strong association of SOC and microbial necromass with short-range ordered minerals underscores the role of mineral−microbe interactions in SOC stabilization. Strikingly, peroxidase activity in Alaskan soils was 1 order of magnitude higher than in Tibetan soils and was tightly correlated with mineral-bound organic carbon. These findings suggest that peroxidase-driven $H_2O_2$ reduction represents a previously unrecognized mechanism of SOC stabilization in Arctic permafrost, with important implications for carbon−climate feedbacks under warming.

**Acknowledgments**

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# Heterogeneity of cryogenic soil cover related to development of patterned ground of Kolguyev Island (Barents Sea)

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**ABSTRACT**

Tundra soil cover is highly heterogeneous at the microscale due to the nearly ubiquitous development of cryogenic patterned ground, including bare-soil circles, stripes, polygons, hummocks, etc. In Russian pedological literature, this phenomenon is described using the terms *cryogenic micropatterns of the soil cover* and *cryogenic soil complexes*.

Cryogenic micropatterns often contain substantial amounts of buried organic matter, part of which may remain frozen; both the quantity and the quality of this organic matter depend on the morphology, shape, and genesis of the microstructure. Patterned ground and the related cryogenic micropatterns, being the result of the combined action of cryogenic and pedogenic processes, are sensitive to climate change. However, estimating soil organic carbon stocks in a highly heterogeneous soil cover is a challenge, as cryogenic soil microstructures possess a complex internal organization.

Thus, the purpose of this study was to assess the current diversity of cryogenic micropatterns and their spatial distribution, providing a basis for subsequent evaluation of soil organic carbon stocks and their potential dynamics.

We developed and tested a methodological approach for describing these micro-heterogeneous soil cover, with particular attention to the internal organization of cryogenic micropatterns. For this purpose, we introduce the term morphotype of a cryogenic micropatterns of the soil cover. During fieldwork on Kolguev Island, we described the patterned ground and associated soil micropatterns, characterized the conditions of their formation.

Nine morphotypes of cryogenic micropatterns were identified in the studied region (Shmatova and Goryachkin, 2025). The spatial distribution of these micropatterns across Kolguev's landscapes *was found* to be heterogeneous: each landscape was characterized by its own unique set, consisting of 2-6 morphotypes. It was also revealed that the degree of heterogeneity of soil cover does not correlate with the expressiveness of surface microtopography. The established dependence of the distribution of micropatterns on lithological and geomorphological conditions provide opportunities for spatial calculations of soil organic carbon.

**Acknowledgments**

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# Needle ice - an antigravity mechanism of cryogenic transformation of soils

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**ABSTRACT**

The formation of needle ice is a widespread, easily observed, but least studied cryogenic process affecting soil properties. Needle ice (NI, pipekrakes) are cryogenic formations consisting of needles of ice up to 10-15 cm high, developing on the soil surface with soil material inside. NI is usually formed on the bare surface of soils due to the migration of soil moisture to the freezing front during night frosts due to the temperature gradient between soil and air. At the same time, active cryoturbation and mechanical transformation of the soil surface occur.

The aim of the study was to characterize the effect of needle ice on the soil properties of the north of Western Siberia (Nadym, Tyumen region, Yamalo-Nenets Autonomous District, Russia). The surface horizons of peat spot soils were studied in the field, and soil samples exposed to NI in a model experiment were studied in the laboratory.

In the field, the surface horizons affected by the NI (0-5 cm) and the underlying ones (5-10 cm) were selected from 5 peat spots. A sample of peat and loam (5-10 cm) was also taken for conducting an experiment in laboratory conditions. For the cultivation of NI, an installation was used that creates a temperature gradient and conditions for the growth of NI. 10 cycles of freezing and thawing of soil samples were carried out, each of which showed the growth of needle ice 3-4 cm high. In parallel, an experiment was conducted with the same samples without the growth of NI (control). The work investigated the general properties and dynamics of labile soil parameters (content of water-extractable carbon and nitrogen (WEOC), basal (BR) and substrate-induced respiration (SIR)).

The results of field studies have shown that the degree of decomposition and ash content increases (by 70%) in horizons exposed to NI. The intensity of BK increases by 40%, and WEOC and microbial biomass – by 2 times.

A laboratory experiment showed that after 10 freeze-thaw cycles, NI had a significant impact on the biological activity of peat soils. As in the field, BR and SIR increased significantly compared to the control (by 22 and 30%, respectively). The content of labile carbon changed slightly, while nitrogen decreased by 40%.

Thus, the formation of NI leads to increased microbiological activity, an increase in microbial biomass, and the rate of consumption of available organic matter, indicating accelerated mineralization of soil organic matter.

# Soils of European Arctic cities under climate change

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**ABSTRACT**

Urbanization is a global trend that leads to irreversible changes in vegetation and soil worldwide. The environmental consequences of urbanization are particularly evident in polar regions, where low temperatures and nutrient-poor soils hinder the restoration and development of ecosystems. The thickness of the seasonal active layer is increasing due to the current warming climate in Arctic cities. The snow-free period is getting longer, making it easier to grow more heat-loving plants (lawn grasses, trees) in polar cities. In the European Arctic, many cities are located outside the cryolithozone, where there is no permafrost. Alternatively, the area of permafrost has decreased, while the thickness of the active layer has increased. At the same time, the frost-free period often lasts less than six months, and stable snow cover remains for up to six months. We studied the morphological structures, chemical properties, and diversity of soils in long-term frozen natural soils (Albic/Entic Podzols and Histosols) and artificially constructed soils (Urbic Technosols) in recreational and residential zones of cities, as well as operating and abandoned settlements in the Kola Arctic Region (Apatity, Monchegorsk, Murmansk, Vaiga-Guba, and Teriberka). These settlements are located outside the permafrost zone. We also used materials from studies in Vorkuta and Naryan-Mar (in the Eastern European Arctic), Barentsburg and Pyramiden (in the Svalbard archipelago), and the Tikhaya Bay polar station (in the Franz Josef Land archipelago).

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# Assessment of Carbon Stocks in Soils ofthe Western Siberian North

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## ABSTRACT

Palsa mires are peat mounds formations located at the southern boundary of permafrost distribution and are vulnerable to climate change. Warming can accelerate the mineralization rate of organic matter, large reserves of which, including in a frozen state, have been accumulating for several millennia. Cryogenic processes (heaving, turbation, cracking) form a heterogeneous soil cover, which complicates its study. A key task is identifying factors that affect soil heterogeneity and carbon cycle parameters, including climate, geology, and biology interactions influencing ecosystem carbon dynamics.

The object of the study is a typical palsa mire complex, within which the following landscapes are located: frost mounds and bog depressions. A total of 110 sampling points were established across 4 $km^2$, where morphological descriptions of soils and geobotanical descriptions were carried out, hydro-thermal parameters of the soils and the thickness of peat horizons were measured, and at some points, $CO_2$ emissions were measured using the chamber method.

Two groups of soils predominate in the territory: oligotrophic peat soils (of various types) – Histosols, and Podzols. Histosols are found everywhere, the Podzols predominantly on mounds. Based on upper soil horizon temperature, two groups were identified: cool flat-palsa peatlands and warm depressions or large mounds. $CO_2$ emission from the soils of the study area varies greatly and is not linked to specific elements of the plant or soil mosaic. The average specific $CO_2$ emission rates for bog soils and peatlands are similar; therefore, the contribution of ecosystems to the total flux depends on their area.

Based on studies assessing carbon stocks in the soils of frost mounds and depressions, conducted within this study area, regression models were constructed to establish a quantitative relationship between peat thickness and carbon stocks for different landscapes. Analysis of data from mounds revealed two distinct clusters. The first includes areas with thick, dense peat and high carbon stocks, for which precise regression equations were developed. The second cluster consists of areas with small thickness peat of low and medium degree of decomposition, where carbon stocks are correspondingly lower; separate models were also developed for them. The depressions are homogeneous according to this criterion. The specific carbon stocks were 471 t/ha on the hummocks and 98.5 t/ha in the depressions.

As a result of interpreting satellite images of the study area, the contours of hummocks and depressions were delineated. After calculating the total areas ofthe typical landscapes, it was found that the total carbon stocks in the soils ofthe hummocks amount to approximately 103,000 tons, and in the depressions, about 7,000 tons.

# Climate-Induced Changes in Soil-Forming Factors and Processes in Permafrost-Affected Areas: Positive and Negative Trends (A Review)

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**ABSTRACT**

A recent compendium of changes in climate parameters and their consequences for ecosystems and human society in cold regions of Russia (Edelgeriev & Ivanov, 2024), as well as relevant internet and published data on other permafrost-affected areas, was analyzed. Climate change, characterized by increased temperature, precipitation, and wind speed, is a notable phenomenon in these regions. However, the response of soil geocryological systems depends on the initial temperature of the permafrost, the depth of the organic layer, and other parameters. Frontal deepening and fractal deepening of soil profiles take place. The latter may be catastrophic, affecting not only the soil but also the landscape. Increased wind speed would intensify wind erosion in some areas and aeolian sand accumulation in others, which is important for sand massifs close to the Arctic coast.

A positive trend is the greening of the Arctic and the northward shift of the treeline. These trends increase biomass, activate carbon turnover in soils, and decrease reductive conditions in soils. Increased biomass productivity in forest stands would result in the northward shift of logging and the development of the forestry industry. However, the growth in the number and size of climate-induced wildfires is a major factor influencing vegetation and soil succession in forests in East Siberia and Alaska. All loamy soils represent various stages of post-pyrogenic development. The intensity and strength of fires determine plant succession types, active-layer thickness, cryoturbation intensity, gleying processes, and the reversibility or irreversibility of soil changes.

Agriculture is not widespread in northern regions, but it is a strong factor in Cryosol transformation because the quantity of agricultural lands is not decreasing but increasing due to the positive effects of climate change on the vegetative period. This can lead to both the deepening and disappearance of permafrost. However, the consequences for the soil depend heavily on the architecture of the cryosystems — ranging from slight positive changes in soils with low ice content to the complete destruction of the soil cover in ice-wedge polygon landscapes.

Therefore, our analysis shows that, in addition to the well-known infrastructure hazards, the negative trends in the consequences of climate-induced changes to permafrost-affected soils outweigh the weak positive trends in high latitudes.

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# The Soil Factors of Palsas Resilience in an Industrial Wasteland in the Arctic Region (Monchegorsk, Russia)

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**ABSTRACT**

Palsas (peat frost mounds) are recognized as important natural indicators of climatic changes (Olvmo et al., 2020). Of particular interest are those located in the heavily polluted industrial barrens near Monchegorsk. Despite the complete loss of vegetation and the covering of dark peat due to acid rain from a nearby metallurgical plant, a frozen core persists within these mounds. The persistence of permafrost in disturbed conditions makes this object a unique phenomenon, of interest for studying the factors ensuring its resilience to climate warming. To determine the causes of this phenomenon, a comparative study of the structure and properties of the peat soils (Cryic Histosols) of a palsa in an industrial barrens and in an undisturbed mire was conducted. The study involved geophysical measurements using ground-penetrating radar, core drilling, and analysis of samples from the active layer. Active layer thickness monitoring revealed seasonal dynamics, increasing from 20 cm in June to 70 cm in September. Our analysis identified three key factors contributing to the palsa's stability in the industrial wasteland: (1) Effective drainage. The mineral base of the peat deposit consists of sands, which provide good drainage. This is critical, as increased peat moisture promotes permafrost degradation (Martin et al., 2019); (2) Microclimate change. Due to the destruction of vegetation, winds have intensified and snow cover has decreased (Kozlov, Zvereva, 2007), which favorably affects the preservation of the frozen core in industrial wasteland. During the cold season, soil freezing accelerated (the temperature at a depth of 40 cm drops below 0°C two weeks earlier than on mounds with vegetation, and thaws 2–3 weeks later); (3) Impact of acid rain. Erosion of the peat has led to increased porosity of the active layer compared to normal conditions (void ratio 15.85 vs 8.83), which has enhanced its thermal insulation properties, for instance, the thermal conductivity coefficient (0.375 vs 0.458 W/m·K). Thus, a unique situation has developed on the Monchegorsk industrial wasteland – anthropogenic impact has generally led to a negative ecological effect, but at the same time has created conditions for the stability of the palsa's permafrost.

**Acknowledgments:**

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# Characterizing Pan-Arctic Soil Organic Carbon: A Comprehensive Database of Particulate and Mineral-Associated Fractions

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**ABSTRACT**

Arctic tundra soils store vast amounts of soil organic carbon (SOC), whose vulnerability to climate change is controlled by the relative partitioning between labile particulate organic matter (POM) and comparatively persistent mineral-associated organic matter (MAOM). Yet, the pedogenic and biogeochemical mechanisms governing this balance and stability remain inadequately constrained at the pan-Arctic scale. We have launched an international collaboration spanning Alaska, Canada, Northern Europe, and Greenland to address this gap. Mineral soils beneath the organic layer are being fractionated using a standardized size-density protocol. For each fraction, we quantify total organic carbon (TOC) and total nitrogen (TN) contents, stable isotopes ($\delta^{13}C$ and $\delta^{15}N$), C/N ratios, and an aromaticity index, thereby assessing organic matter quality and inferring fraction-specific stabilization pathways. Here, we present the compilation of these experimental datasets, integrated with a meta-analysis of published studies, to establish a comprehensive circumpolar database of POM and MAOM properties. Using this synthesized database, we aim to apply data-driven and machine-learning approaches (e.g., decision trees and random forests) to explore the climatic, edaphic, and biotic variables that predict SOC partitioning and fraction-specific chemistry. This framework serves as a foundation to identify when and where SOC is stabilized as MAOM versus retained as POM, providing a basis to anticipate SOC vulnerability under warming, altered snow regimes, and vegetation shifts. By uniting standardized fractionation protocols with scalable analytics, our efforts contribute to advancing pan-Arctic, mechanism-informed predictions of Arctic carbon fate in a rapidly changing world.

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# Vertical Distribution of Methane Concentration in Permafrost-Affected Soils of Central Yakutia

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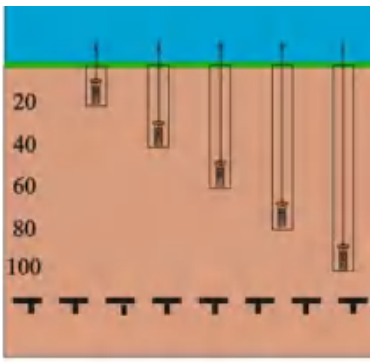
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**ABSTRACT**

Thermal permafrost degradation promotes increasing $CH_4$ emissions from soils owing to either bacterial decompositon of thawing soil organic matter or release from thawing massive ground ice containing dissolved methane and gas bubbles. On the other hand, an observed increase in air and land surface temperature might lead to decreasing soil humidity and favoring methanotrophy in the active layer. Three monitoring sites were organized in 2021-2022 in typical landscapes of Central Yakutia, Northern Eurasia, to observe vertical distribution of $CH_4$ concentrations in gaseous phase of permafrost-affected soils. Air sampling was performed using soil pipe technique, described in (Smagin, 2005). Soil air inlets were installed at 0.2m, 0.4m, 0.6m, 0.8m and 1.0m depths along with plastic tubes going up to the ground surface, as shown in the figure. Soil air was sampled in plastic 50ml syringes, transferred to glass vials pre-filled with saturated NaCl solution and transported to the laboratory. Methane concentration in samples was measured by gaz chromatography at Obukhov Institute of Atmospheric Physics.




In spruce forest (Kyiuy site) $CH_4$ concentration is found to vary from 1 to 2 ppm in top-soil (0.1-0.2m) and gradually decrease to 0.3-0.5 ppm down the profile. In larch forest (Sullalr site), significantly higher interannual variability was observed. In dry year (2022) the $CH_4$ distribution resembled that of Kyiuy site, but in wetter years the $CH_4$ concentration in top-soil increased up to 7-36 ppm, suggesting that saturated top-soil layer reduces methanotrophic potential and blocking $CH_4$ release to the atmosphere.

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# Assessment of soil temperature dynamics in different soil landscapes in western Greenland

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**ABSTRACT**

Soils in periglacial environments, such as those in western Greenland, store large amounts of organic carbon that have accumulated under persistently cold conditions and reduced biological activity. Kangerlussuaq, located in western Greenland at the head of a fjord adjacent to the Greenland Ice Sheet, constitutes the largest ice-free region in Greenland. This area is of considerable scientific interest due to its complex climatic history, characterized by cooling during the early 20th century followed by pronounced and accelerated warming in recent decades. The present study aims to evaluate soil temperature dynamics across different pedolandscapes in western Greenland. During the 2024 field campaign, three soil temperature monitoring stations were installed in proximity to selected soil profiles. Temperature sensors were deployed using an earth auger at depths of 10, 50, and 130 cm below the soil surface. Each sensor was programmed to record temperature at six-hour intervals, resulting in four measurements per day at each depth and enabling continuous long-term monitoring. Temperature data collected between summer 2024 and summer 2025 were retrieved during the subsequent field campaign, yielding a complete annual record. Monthly mean soil temperatures were calculated for each depth. In addition, several thermal indicators were derived, with adaptations to account for the temporal resolution of the measurements: Thawing Days, Freezing Days, Isothermal Days, Freeze–Thaw Days, Thawing Degree Days (TDD), and Freezing Degree Days (FDD). The results reveal pronounced spatial heterogeneity in active-layer thermal regimes over short distances, likely reflecting variations in vegetation cover, soil moisture, and surface energy balance. All monitored profiles exhibited at least one full month with mean temperatures above 0.5 °C, indicating sustained thawing conditions, while all soil layers also experienced at least one complete month with temperatures below −0.5 °C, corresponding to fully frozen conditions. A strong vertical thermal contrast was observed, with high thermal amplitudes in surface layers, contrasting with colder and more buffered subsurface layers characterized by a high frequency of isothermal days, particularly at 30 cm depth. These thermal patterns suggest a bidirectional control of soil temperature on organic matter decomposition along the soil profile, with surface layers responding rapidly to seasonal forcing and deeper layers exhibiting delayed and dampened thermal responses. Overall, thermal monitoring revealed marked seasonal and vertical variability in soil temperature regimes. While surface layers underwent large annual temperature amplitudes, including extended thawed periods during summer and prolonged freezing during winter, subsurface layers displayed more stable thermal conditions, with numerous isothermal days and site-specific differences in thawing and freezing dynamics.

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# Soil structural transformation under multiple freeze-thaw cycles with comprehensive morphological and topological analysis: the hypothesis of periodicity

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**ABSTRACT**

Freezing-thawing cycles significantly affect the dynamics of soil pore space structure, both directly and through indirect processes. Previous studies have reported varying observations and interpretations regarding the qualitative and quantitative changes in soil structure induced by these cycles. In this study, we conducted freeze-thaw experiments on three different disturbed soil samples. The samples were imaged with an X-ray scanner in their original state and after 1, 5, 10, and 20 freeze-thaw cycles. To process the obtained data, we employed two novel but essential methods:

(1) a custom-built image registration technique to establish identical 3D regions of interest within the scans, and (2) a set of soil structural descriptors with high information content, incorporating both morphological and topological information—correlation functions, pore-network statistics, Euler numbers, and connectivity.

(2) Registration and careful consideration of individual grains within the soil structure enabled robust segmentation of grayscale images into solids and pores.

Unlike most previous studies, we did not observe a steady or nearly monotonic change in structural metrics. Instead, we detected a type of chaotic behavior of these metrics between the freeze-thaw cycles. Using vector descriptors, we demonstrated that the experimental data can be interpreted as hypothetical oscillatory changes within soil structure. This finding leads us to hypothesize that disturbed soils—and possibly natural soils after multiple cycles—undergo periodic structural dynamics. The novel idea behind this hypothesis is simple: as at some point the same temperature impact will not produce the same effect, the structure disturbance will stagnate. From the original state, soils exhibited the strongest structural degradation due to freeze-thaw cycles, whereas in subsequent cycles the dynamics involved both dispersing and aggregating processes, as observed in the X-ray tomography images. We conclude by discussing the necessary future research to confirm or refute this hypothesis and emphasize why soil structure in such experiments should be described using a novel class of vector metrics with high information content, which also subsume most classical soil structural metrics.

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# Organic-matter rich soils hidden inside alpine periglacial blockfields: paleosols or aeolian deposits?

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## ABSTRACT

Permafrost warming due to rising global temperatures has the potential to alter carbon (C) cycling in high-mountain environments, yet alpine permafrost regions remain poorly studied compared to Arctic systems. In particular, coarse blockfields on alpine summits (>2900 m a.s.l.), often vegetation-free and traditionally assumed to be devoid of soil organic carbon (SOC), may conceal previously unrecognized carbon stocks. To address this gap, we investigated SOC occurrence, stocks, age, and composition in alpine blockfields across the Swiss and Italian Alps.

On nine mountain tops (2900–3350 m a.s.l.) within the periglacial zone (with the addition of a low-elevation fossil Pleistocene blockstream at ca. 1200 m a.s.l.), we removed a layer up to more than one meter thick of coarse blocks and described 18 soil profiles hidden below. Some of the sites were completely barren, while in others a few plants grew between the stones or in the central parts of sorted patterned ground morphologies. Weakly decomposed plant fragments of aeolian origin were found at the base of the stone layer in six soil profiles. Below, the observed soils showed dark brown to black A horizons with thickness between few and 62 cm, overlying Bw, Bs or C horizons. The texture was usually sandy loamy to loamy sand, with very few stones, and the pH was usually acidic to strongly acidic. In different sites, soils could be classified as Akroskeletic Cambic Umbrisols, Dystric Akroskeletic Cambisols, Akroskeletic Regosols, and one as an Akroskeletic Entic Podzol.

In the A horizons, the C content was between ca. 3.2 and 37.2 g $kg^{-1}$, usually with C/N ratios between 8 and 15, indicating well-decomposed organic matter. The C stocks were significant, considering the barren landscape of blockfields, and they were between 0.8 and 10 kg C $m^{-2}$. The soils showing the strongest weathering degree like the Umbrisols, Cambisols and the Podzol (likely predating the Holocene) had the largest C stock.

Radiocarbon dating revealed that plant fragments were mostly recent, while the humic materials in the dark A horizons ranged between ~4,000 years near the surface to ~12,900 years at depth, with some extreme values (17,000 and 22,000 years) in a Monte Rosa massif blockfield. Between 65% than 90% of organic carbon was stored in a stable mineral-associated organic matter pool, highly decomposed and dominated by lipids, waxes, cellulose, and hemicellulose. Thin section observations under optical microscope and SEM-EDS images verify the strong decomposition degree of such humified material. Although the aeolian origin of the soil was well visible in one site (Venerocolo summit, Adamello massif), the organic matter composition did not allow us to distinguish an aeolian pool, and one originated from ancient alpine tundra vegetation that developed during warmer climatic phases. Together, these findings demonstrate that alpine blockfields and periglacial features can host substantial, millennia-old, and largely stable SOC pools, preserved for long times by cold soil temperatures and metal-organic stabilization. These "hidden" carbon reservoirs likely formed through a combination of Holocene vegetation inputs and atmospheric deposition and may become vulnerable to mobilization under future climatic warming, with implications for alpine carbon–climate feedbacks.

# Soil organic carbon stock assessment in cryoturbated turf/grass mounds in Kobresia Medows, Qinghai-Tibetan Plateau)

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**ABSTRACT**

Soil organic carbon (SOC) is a critical component of terrestrial ecosystems, serving as a key indicator of soil health and ecosystem function. Despite growing research on SOC estimation at regional, national, and global scales, accurately quantifying SOC in the Arctic and alpine regions remains challenging due to periglacial features. These features include sorted and nonsorted circles, earth hummocks, turf mounds and ice wedge polygons and other features formed due to cryoturbation. To overcome the high special heterogeneity caused by these features, the pedologists and geocryologists have developed the approach of applying the pedon concept to sample the soils across those periglacial features in the past decades. To take an example of the nonsorted circles (frost boils), the pedon is defined from the center of the circle to the center of the depressed area between the circles, as called “inter-circles”. The dimension of the pedon can be from 1 m to 3.5m wide and depth to 3m or as limited by paralithic or bedrock contact, or massive ice. Thus, for the turf hummocks dominated by Kobresia, the pedon is defined from the center of the hummocks to the centers of the depressions in between the hummocks. The soil horizons or zones on the exposed profile are delineated and the percentage of each zone of the whole profile is calculated. The C density of the whole profile is calculated by the summation of the percentage of the C storage of each zone expressed as kg/m$^3$.

**References**

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# Mattic layer ruptures in the Third pole: mechanisms, distribution, consequences, and monitoring

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**ABSTRACT**

The mattic layer (ML), a dense root-soil matrix formed predominantly by Kobresia sedges, constitutes a keystone pedogenic feature governing ecosystem functioning across 2.5 million km² of the Qinghai-Tibetan Plateau. However, the ML rupture as widespread structural failures now threaten this vital ecological barrier, initiating cascading degradation with far-reaching implications for carbon cycling, hydrology, and biodiversity. This review provides the first comprehensive synthesis of ML ruptures through an integrated framework from formation, distribution, and consequences, to monitoring. Contemporary ruptures manifest as five distinct morphotypes driven by synergistic anthropogenic and natural factors. Anthropogenic drivers include overgrazing exceeding carrying capacity by 50-165%, infrastructure development, and resource extraction. Natural drivers encompass climate warming at 0.31-0.39°C per decade, permafrost degradation, intensified freeze-thaw cycles, and biotic disturbances. These factors generate self-reinforcing feedback loops that push systems beyond recovery thresholds. Consequences cascade from immediate soil degradation through hydrological disruption to transformation of carbon sinks into sources, and social-economic impacts at both the local and global scale. The ML rupture represents more than just regional degradation; it fundamentally alters carbon cycling and climate regulation with impacts extending from pastoral livelihoods to global systems. The monitoring of ML rupture has evolved from conventional field investigations to integrated remote sensing and in-situ sensor networks, enabling unprecedented spatiotemporal resolution for tracking ML rupture dynamics. Despite extensive research on individual components, critical knowledge gaps persist regarding formation-rupture linkages, threshold dynamics, and the synergistic interplay of multiple drivers. This synthesis establishes a scientific foundation for understanding ML responses to global change and developing targeted conservation strategies for these irreplaceable alpine ecosystems facing unprecedented environmental pressures.

# Study on the coupling relationship between agricultural water and soil resources carrying capacity and grain production capacity in typical black soil regions of Northeast China

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**ABSTRACT**

The Northeast Typical Black Soil Region (NETBSR), a vital grain production base in China, has long played a critical role in safeguarding national food security. However, intensive agricultural practices, climate change, and unsustainable resource utilization have collectively challenged the carrying capacity of its agricultural water-land resources, threatening regional food production sustainability. This study employs the DPSIR (Driving Forces-Pressure-State-Impact-Response) framework to establish a comprehensive evaluation system for agricultural water-land resource carrying capacity (AWRCC). Using entropy-weighted TOPSIS modeling, we systematically assessed the spatiotemporal evolution of AWRCC in NETBSR from 2002 to 2022. The Miami model and spatial analysis techniques were integrated to estimate grain production potential, quantify spatial coupling relationships between AWRCC and production capacity, and analyze correlations with actual yields. Key findings include:

1. AWRCC exhibited marked spatiotemporal dynamics, increasing from 0.38 to 0.64 during 2002–2022. A slight decline occurred during 2002–2007 due to overexploitation of arable land, followed by accelerated growth (2008–2015) driven by black soil conservation policies and water-saving agriculture. Post-2016, growth stabilized, yet regional disparities persisted, with the Songnen Plain consistently outperforming other subregions.
2. Grain production capacity rose from 5,800 to 7,300 kg/ha, demonstrating pronounced spatial heterogeneity. High-yield zones (7,500 kg/ha in Songnen Plain; 7,200 kg/ha in Sanjiang Plain) contrasted with low-yield areas (6,000–6,200 kg/ha in Heihe and Jixi), influenced by policy shifts, climatic variability, and land-use patterns.
3. While a significant positive correlation is observed between agricultural water and soil resource carrying capacity and grain production capacity at the overall level ($r = 0.67$), temporal and spatial fluctuations indicate phases of coupling imbalance in specific years and regions. This relationship was especially strong in the Songnen Plain region ($r > 0.75$). In contrast, the correlation with actual grain output was weaker ($r = 0.42$), suggesting that grain production is influenced not only by resource endowment but also by external factors such as market demand, policy shifts, and cropping structure transformation.
4. Precipitation, primary output value and the proportion of high water-consuming crops are the main obstacles to the carrying capacity of regional agricultural water and soil resources. Notable differences in barrier structures were observed across regions with varying levels of grain production potential. By identifying critical constraints and proposing differentiated management strategies, this study provides theoretical support and practical insights for enhancing agricultural sustainability and grain productivity in the black soil region of Northeast China.

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# Study on the coupling relationship between agricultural water and soil resources carrying capacity and grain production capacity in typical black soil regions of Northeast China

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## ABSTRACT

The black soils in Northeast China are the main production area of grain crops in China and are of great significance to ensuring national food security. However, the black soils in this region have been degraded due to long-term high-intensity utilization and climate change. Soil "hardening" is an important factor of declining arable land quality in this region. Although many studies have increasingly paid attention to the degradation of soil organic matter and nutrients in black soils, the systematic understanding of the key factor of soil "hardening" and their spatial distribution pattern are still relatively insufficient in the black soils in Northeast China. At the same time, the lacks of measured bulk density data in the existing soil database have led to be difficulty in assessment the accuracy of large-scale soil "hardening". Although the random forest model is widely used in soil property prediction, its application for spatial prediction and mapping in soil bulk density is still relatively scarce. Therefore, it is of great practical significance to clarify the spatial distribution pattern and driving factors of soil bulk density and compactness of typical black soil in Northeast China, and to explore the establishment of soil bulk density transfer function. So this study takes the black soil in Songnen Plain as the research object, combines field surface soil survey with soil profile survey, and comprehensively uses geographic detectors, random forests and other methods to explore the spatial distribution characteristics of soil bulk density and compactness in the Songnen Plain, and explore the main influencing factors of key indicators of soil "hardening", and further construct the transfer function between soil bulk density and other soil properties, in order to provide a scientific basis for the rapid diagnosis of the degree of "hardening" of black soil in the region. The main research results were as follows:

(1) The variation characteristics of soil bulk density and compaction in the surface and subsurface layers of different soil types were different. Black soil, meadow soil and dark brown earth showed different variation patterns with depth. The variation trend of soil bulk density of black soil with depth was relatively stable, and the power function model had a better fitting effect ($R^2$=0.63); the variation range of soil bulk density of meadow soil with soil depth was relatively large; the soil compaction of dark brown earth increased significantly with the increase of profile depth, and the power function model had the best fitting effect ($R^2$=0.89).

(2) The spatial distribution of soil bulk density and compaction in the black soil region of the Songnen Plain was characterized by regional variability. Prediction mapping showed that soil bulk density exhibited an overall increasing trend from north to south, with higher subsurface bulk density observed in the southern and central areas (e.g., Songyuan and Siping). In contrast, surface and subsurface soil compaction was found to be relatively higher in the northern and northwestern parts of the region (e.g., Hulunbuir and Heihe), indicating a certain degree of spatial divergence between the two. However, spatial consistency between bulk density and compaction was observed in areas such as eastern Harbin and southeastern Suihua.

(3) The spatial variation of soil bulk density and compaction was influenced by multiple factors, including soil organic matter content, and interactions among these factors were observed. Soil organic matter content was found to have a strong explanatory power for both surface and subsurface bulk density. The interaction between soil organic matter and mean annual temperature provided the highest explanatory power for surface bulk density ($q$=0.51). In terms of soil compaction, water content exhibited strong combined effects with other variables, with the interaction between water content and mean annual temperature showing the strongest explanatory power ($q$=0.53).

(4) Support vector machine, binomial and generalized linear model methods are effective in constructing bulk density transfer functions based on soil organic matter and compaction. Among these, the binomial model and support vector machine demonstrated higher accuracy and stronger explanatory power when fitting the relationships between organic matter and bulk density ($R^2$=0.43), as well as compaction and bulk density ($R^2$=0.56). In addition, the transfer function constructed based on soil compaction performed better in the subsurface layer ($R^2$=0.56).

The results indicated that the spatial distribution of soil bulk density and compaction in the black soil region of the Songnen Plain was characterized by regional differences. These differences were influenced by both natural and anthropogenic factors, among which soil organic matter content was identified as the primary influencing factor, and interactions with climate and topography were observed. The support vector machine and binomial regression models were found to perform better in predicting soil bulk density, especially when the transfer function was constructed based on soil compaction in the subsurface layer. This demonstrated the potential of compaction-based models for rapid diagnosis of soil "hardening" in black soil regions.

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# Integrating Remote Sensing and Soil Drainage Mapping to Predict Salinization Risk

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**ABSTRACT**

Salinization is a major threat to agricultural sustainability, particularly in semi-arid regions where salt accumulation degrades soil quality and limits crop productivity. Existing salinization risk maps often rely on outdated, polygon-based datasets that oversimplify spatial variability and fail to capture emerging risk zones. To address this gap, this study developed a high-resolution, raster-based salinization risk tool using remote sensing and terrain analysis. A key innovation of the approach is the integration of a newly developed drainage classification model as an input for assessing salinization risk. Using remotely sensed imagery and terrain variables derived from a 5-m digital elevation model (DEM), a Support Vector Machine (SVM) model was trained to classify soil drainage, achieving a Kappa coefficient of 0.64, with sensitivity values of 0.82 for well-drained, 0.87 for poorly drained, and 0.50 for very poorly drained areas. The resulting drainage layer, along with four other key salinization drivers (aridity, surface cover, current salinity, slope) were weighted using Grey Relational Analysis and ranked based on their relative influence on salinization. These ranked inputs were then combined to produce a spatially explicit salinization risk map, enabling more detailed and actionable identification of at-risk zones at the field scale.

# Geostatistical fusion of field and remote sensing data for assessing soil salinity in southern region of Morocco

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**ABSTRACT**

Soil salinization is the process of accumulation of water-soluble salts within the upper part of soil profile (particularly A and B horizons). Salinization originates from different sources and is one of major worldwide soil threat which rarely comes alone. Therefore, quantifying and spatial modelling of indicators of salinization is crucial to manage and mitigate the soil salinization process. The use of remote sensing in mapping and assessment of soil salinization represents the possibility of achieving ever greater spatial resolution. Particularly in conditions where it is difficult or too much expensive field measurements or collecting soil samples. One of this case is presented in this study in a southern region of Morocco. 490 samples were taken from these regions from 0 to 20cm depths The sampling method was designed to capture the maximum variability across all the study areas while ensuring the homogeneity of samples in each sub-region. 490 samples were taken from these regions from 0 to 20cm depths.

A crucial problem to be solved to use spatial data of different nature and characteristics such as field and remote sensing data is the support of measurement, which is very different between the types of data. Therefore, to solve this issue and derive the maximum information, it is necessary to apply appropriate techniques of spatial statistics by defining a spatial statistical model. In this study, a multivariate geostatistical approach is proposed that can fuse data of different types, including soil sample satellite data, to model and map soil electrical conductivity considering the various supports and their impacts on prediction. Remote sensing data consists in pixels which are considered as the average reflectance of light from a limited support. Therefore, decomposing the original support into a set of finer supports was necessary to combine field and remote sensing data.

# Study on Soil Organic Matter Inversion of Different Textural Soils in the Northeast Black Soil Region Based on Hyperspectral Remote Sensing

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**ABSTRACT**

Considering that the ability of hyperspectral estimation of soil organic matter is influenced by soil texture, grouping soil samples according to texture is a strategy to improve prediction accuracy. This study takes Heilongjiang, Jilin, Liaoning provinces, as well as Hulunbeir City, Xing'an Prefecture, Tongliao City, and Chifeng City in Inner Mongolia as the research areas, with 347 soil samples as the research objects. Based on the United States Department of Agriculture (USDA) soil texture classification standards, the samples are divided into four groups: sandy soil, loamy soil, loamy clay, and clay, and a control group without distinguishing soil texture is set up. Firstly, the spectral reflectance characteristics of total samples and four groups of samples with different textures are systematically analyzed. Secondly, after comparing various spectral preprocessing methods, the Multiple Scatter Correction + Savitzky-Golay (MSC+SG) method is selected as the optimal preprocessing scheme based on the Pearson correlation coefficient. Then, the Competitive Adaptive Reweighted Sampling (CARS) and Successive Projections Algorithm (SPA) are used to screen characteristic bands, and the similarities and differences of characteristic bands among different soil samples are analyzed. Subsequently, Random Forest (RF) and Partial Least Squares Regression (PLSR) are employed to construct inversion models, and the accuracy of the models is verified and evaluated. Finally, based on the spectral reflectance characteristics and characteristic bands of different soil samples, remote sensing images are used for comparative analysis, and organic matter distribution maps are drawn. The main research results are as follows: (1) When soil texture is not distinguished, the PLSR constructed by MSC+SG combined with CARS-SPA has the best inversion effect on hyperspectral organic matter in soil, with a coefficient of determination ($R^2$) of 0.67, a root mean square error (RMSE) of 11.45, and a relative analysis error (RPD) of 1.67. (2) When soil texture is distinguished, the optimal inversion model for all four groups of soil is MSC+SG-PLSR, with $R^2$=0.99 and RMSE=1.21 for the sandy soil group, $R^2$=0.52, RMSE=12.26, and RPD=1.47 for the loamy soil group, $R^2$=0.85, RMSE=6.07, and RPD=2.69 for the loamy clay group, and $R^2$=0.66, RMSE=9.10 for the clay group. The inversion accuracy is significantly improved compared to when soil texture is not distinguished. This indicates that soil texture in the black soil region of Northeast China has a significant impact on the accuracy of hyperspectral inversion of organic matter. This study provides technical support for monitoring soil organic matte content in the black soil region of Northeast China.

# An airborne platform for enhanced soil characterization

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**ABSTRACT**

Advances in remote sensing have transformed the way soils are monitored, mapped, and managed for agricultural productivity. Soil properties such as texture, moisture, organic matter, and nutrient status vary across landscapes, influencing crop performance and resource-use efficiency. Accurate and spatially resolved measurements of these properties are therefore essential for precision agriculture, where site-specific management decisions depend on detailed knowledge of soil variability.

This work introduces the development and planned application of an airborne platform aimed at improving soil characterisation for precision agricultural use. The system integrates multispectral imaging, radiometric measurements, and geospatial positioning to enable the rapid collection of surface and environmental data across extensive and often inaccessible agricultural landscapes. By capturing reflectance patterns and associated environmental signatures, the platform is designed to facilitate the estimation of key soil parameters relevant to crop health, resource-use efficiency, and land-management planning.

The presentation will outline the system architecture, survey design, and planned analytical workflows for processing airborne data and generating spatially detailed soil maps. These workflows are intended to reveal patterns in soil condition, support the delineation of management zones, and guide targeted interventions such as variable-rate fertilisation and irrigation scheduling. The platform's flexible and repeatable deployment is expected to enable ongoing monitoring of temporal changes in soil status and to strengthen decision-making in precision agriculture. Overall, the approach has strong potential to enhance agricultural monitoring, improve resource-use efficiency, and support sustainable land management and long-term soil health.

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# Intelligent Monitoring of Soil Salinization by Integrating Agronomic Features

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**ABSTRACT**

Soil salinization is one of the major soil degradations that threats agricultural production and food security, particularly in arid and semi-arid regions. Remote sensing is an important tool for monitoring soil salinity information on a large scale. Although remote sensing allows for the soil salinity mapping by analyzing the spectral responses of soil and vegetation, a common limitation is the oversight of field management practices, which are known to significantly influence soil moisture dynamics and salinity accumulation. Compared to healthy cropland, saline cropland requires distinct field management practices, such as higher salt-tolerant crops and higher irrigation demands. Consequently, field management information represents a potent indicator for soil salinity mapping in cropland, yet it remains overlooked in related researches.

This study addresses this gap by integrating novel agronomic features—crop planting structure and irrigation indicator—into salinity prediction models. Crop planting structure was a quantitative representation of crop classification results using target encoding. The irrigation indicator was derived from the Temperature Vegetation Dryness Index (TVDI) to capture seasonal soil moisture variations associated with irrigation during the growing season. Lastly, we established a predictive model of soil salinity content using Extreme Gradient Boosting (XGBoost). The variables were grouped into several combinations to explore the effects of different feature types. We chose a typical region with frequent agricultural activities in the arid and semi-arid climate zone in northwestern China.

Our results demonstrate that incorporating these features significantly improves model performance compared to conventional models using only environmental and spectral variables. The coefficient of determination ($R^2$) increased by 0.11 reaching 0.74. Notably, crop planting structure emerged as the most influential predictor, underscoring the value of field management information in cropland salinity mapping. Future research will explore advanced spatial representations of management practices, such as the distribution of irrigation infrastructure and continuous cropping years, to further enhance predictive reliability in soil salinity mapping.

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# Integrating UAV-Mounted Gamma-Ray Spectrometry and Soil Laboratory Analysis to Characterize Sediment Erosion, Composition, and Pollution in Vineyards

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## ABSTRACT

Comprehending fine-scale soil variability is crucial for enhancing vineyard management within precision agriculture, because spatial heterogeneity in soil properties and erosion dynamics directly influences vine water availability, nutrient cycling, and the long-term soil functionality. Soil contamination is a multifaceted process that jeopardizes ecosystem services and agricultural sustainability, emphasizing the need for rapid, spatially comprehensive diagnostic methods such as proximal or remote radiometric sensing. This study investigated the potential of unmanned aerial vehicle (UAV)–mounted gamma-ray spectrometry (GRS) to map soil texture, characterize primordial radionuclide activities ($^{40}$K, $^{238}$U, $^{232}$Th), and trace sediment-erosion processes across a commercial vineyard. High-resolution radiometric measurements were acquired using a lightweight scintillation detector flown at low altitude (≤5 m), enabling detection of natural gamma emissions associated with mineralogical composition and the redistribution of surface materials. Soil gamma radiation frequently shows robust correlations with texture, as radionuclides are structurally incorporated into specific minerals (e.g., K in illite and mica), adsorbed onto the soil's cation-exchange complex, or immobilized within Fe–Mn oxides and other heavy mineral fractions. These relationships allowed radiometric variations to serve as indirect indicators of textural gradients. Additionally, spatial deviations in radionuclide activities acted as tracers of soil erosion, reflecting the selective removal and deposition of fine particles along the landscape. After applying corrections for flight altitude, soil moisture, and detector response, spectral analysis was conducted to derive radionuclide enrichment patterns linked to soil movement, textural gradients, and potential contamination pathways. Ground-truth soil samples were collected for laboratory analysis of texture, radionuclide concentrations, and organic and inorganic soil constituents. Both the in-situ measurements and laboratory datasets were interpolated using Geographic Information Systems (GIS)–based Inverse Distance Weighting (IDW) to generate continuous spatial surfaces for comparison with UAV-derived radiometric maps. These interpolated layers were used to refine predictive modelling frameworks and improve interpretation of erosion signatures, radionuclide redistribution, and contamination trends. The integration of UAV data with in-situ observations, laboratory assays, and modelling frameworks enhanced the capacity to map degradation patterns and assess recovery trajectories within the vineyard landscape. The resulting spatial products revealed soil zones shaped by parent-material variability, slope-controlled sediment transport, and management-related disturbances. Overall, the study demonstrated the potential of UAV-borne gamma-ray spectrometry as a rapid, non-destructive tool to support targeted soil amendments, erosion-mitigation strategies, and sustainable precision agriculture in viticultural systems.

# Soil Reflectance Composite and Terrain Attributes for Digital Soil Mapping in a Mediterranean Cropland District

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**ABSTRACT**

Accurate soil maps are essential for soil protection, policy implementation, and digital agriculture. However, traditional soil maps often lack the detail required for local applications, while farm-scale surveys are often not economically sustainable.

This study was carried out within Rieti plain, an important agricultural area of about 40 km2 in central Italy (Zanini et al., 2024). Legacy soil data and digital soil mapping (DSM) were used to produce accurate, low-cost maps of key soil properties, namely clay, sand, total lime (CaCO3), organic carbon (SOC), total nitrogen (TN) and cation exchange capacity (CEC). The DSM procedure involved Multivariate Stepwise Regression Kriging that uses terrain attributes and bare soil reflectance composite (SRC) from Sentinel-2 multi-temporal images. SRC was obtained using the Soil Composite Mapping Processor (SCMaP), an automated methodology for extracting the reflectance of bare soil pixels of each image . The SRC map was then created by calculating the average of the extracted bare soil pixels, between 19 and 391 dates over a five-year period (2018-2022). The SRC map of all of Europe is now available as e.g. a WMS service at https://geoservice.dlr.de/eoc/land/wms (Heiden et al., 2025).

The Sentinel-2 bands of SRC showed strong correlations with topsoil features (A horizon), making them highly suitable explanatory variables for regression kriging. In particular, the SWIR bands (b11 and b12) were key in predicting clay, sand, and CEC maps. The regression models were highly accurate for clay, sand, SOC, and CEC ($R^2 > 0.90$), but showed lower accuracy for CaCO3 ($R^2 = 0.67$). Similar results were obtained when predicting subsoil (B horizon) clay and sand content, probably for the cross-correlation between topsoil and subsoil features.

Additionally, a supervised classification approach was applied to predict Soil Typological Units (STUs) based on the mapped soil attributes and STU classification in the described profiles. This methodology demonstrates the potential of SRC and regression kriging for producing detailed soil property maps to support precision agriculture and sustainable land management.

**Acknowledgments**

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# Localized SCORPAN-based machine learning framework for spatial-temporal tracking (2000–2025) of soil carbon dynamics in Chile

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## ABSTRACT

Digital soil mapping (DSM) enables spatially and temporally explicit prediction of soil attributes relevant to agricultural sustainability and carbon accounting. This study developed an integrated workflow to predict soil organic carbon (SOC) stock from 2000–2025 using a SCORPAN-based covariate framework and machine learning. A harmonized soil database of >12,000 data point (0–30 cm) from Chile supported model calibration. Static covariates included terrain attributes (GEDTM30), long-term climate (WorldClim, aridity index), soil class probabilities (SoilGrids), geomorphology, oblique coordinates, and distance to water bodies. Dynamic covariates were derived annually from Landsat Collection 2, including reflectance bands, vegetation indices (NDVI, NDWI, NDSI), spectral unmixing fractions, and temporal trend metrics based on Sen's slope. Additional dynamics included annual ERA5-Land climate variables, MODIS LST (day/night), and land-use intensity. All covariates were resampled at 30 m resolution. Localized models were developed using LightGBM, optimized via halving grid search cross-validation, and trained separately for OM and BD using region-specific data weighted by inverse distance to the geomorphological strata covering the study area. Model performance was evaluated using independent train–test splits and $R^2$, RMSE, MAPE, RPIQ, and Lin's concordance (CCC). OM prediction achieved $R^2 = 0.70$, RMSE = 2.79%, CCC = 0.82, and RPIQ = 4.49. BD predictions showed stronger performance ($R^2 = 0.83$, RMSE = 0.09 g $cm^{-3}$, CCC = 0.91, RPIQ = 7.36). Optimized models were applied to generate space-time annual predictions from 2000 to 2025. SOC stock (t C $ha^{-1}$) was computed from SOC (OM*0.58) and BD predictions, ensuring equivalent mass-based comparison across time. Temporal analysis of SOC stock revealed clear declining trends across the area. Mean SOC decreased at −0.66 t C $ha^{-1}$ $yr^{-1}$, the 95th percentile at −0.73 t C $ha^{-1}$ $yr^{-1}$, and the median at −0.49 t C $ha^{-1}$ $yr^{-1}$. Even the lower bound (5th percentile) showed a modest decline of −0.03 t C $ha^{-1}$ $yr^{-1}$. These consistent negative slopes indicate widespread SOC losses over the 25-year period, with higher-SOC areas presenting the strongest declines. The resulting maps show pronounced spatial and temporal variability in SOC stocks, driven by land management and environmental gradients. Space-time maps can be explored via the Soil Explorer web interface (https://geospatial-425519.projects.earthengine.app/view/soil-explorer). The proposed SCORPAN–ML workflow provides a robust, scalable framework for high-resolution DSM and supports precision agriculture, carbon monitoring, and sustainable land-use planning.

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# Accurate Time-Series Retrieval of Soil Salinity from CYGNSS Data by Physics-Based Surface Correction and Semi-Empirical Model

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## ABSTRACT

Soil salinization is a key factor impeding agricultural sustainable development; thus, accurately acquiring large-scale time-series soil salinity information is of great significance for ensuring national food security. As a pivotal element of the spaceborne Global Navigation Satellite System Reflectometry (GNSS-R) mission, Cyclone Global Navigation Satellite System (CYGNSS), with its advantages of high spatio-temporal resolution and strong penetration capability, can extract soil salinity information mechanistically without relying on in-situ samples. However, complex surface effects and the confounding influence of moisture on the soil dielectric constant constitute the pivotal scientific challenges limiting high-precision CYGNSS soil salinity retrieval. Based on CYGNSS data, this study proposed a novel soil salinity retrieval model (PRD) through two primary steps: First, a combined surface attenuation correction method rooted in microwave radiation principles was established. The resulting corrected surface reflectivity demonstrated good consistency with soil moisture data from Soil Moisture Active Passive (SMAP) (R=0.84). Second, this surface reflectivity was fused with an improved soil dielectric constant model to uncover the bridging mechanism of soil dielectric properties in soil salinity retrieval. The PRD model's accuracy was subsequently validated using in-situ soil salinity data and compared to the CYGNSS empirical correction (ERD) model. Validation confirmed the PRD model's superior performance, achieving the coefficient of determination ($R^2$) of 0.83, the root mean square error (RMSE) of 0.53‰, and the ratio of performance to deviation (RPD) of 2.33. The spatio-temporal dynamics of soil salinity in the Yellow River Delta in 2023, derived from the PRD model, revealed a climate-driven seasonal cycle: Salinity peaked at 4.75‰ in May (accumulation phase) and reached its minimum at 2.35‰ in July (leaching phase). High-salinity zones were concurrently observed to be structurally fixed along the coastline and inland depressions. In essence, these findings establish the PRD model's feasibility and capability as an accurate, physics-informed framework for advancing continuous, large-scale soil salinization monitoring using GNSS-R technology.

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# Explainable Deep Learning Unveils Critical Scenarios Driving Soil Cadmium Pollution in a Coastal Industrial City: A Geospatial AI Approach

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## ABSTRACT

Traditional soil heavy metal source apportionment relies on point-based chemical analysis, which often overlooks the critical influence of spatially continuous landscape patterns on pollution distribution. This study proposes an innovative approach, developing an explainable geospatial AI framework to directly infer the likelihood of exogenous cadmium (Cd) contamination from landscape features within remote sensing (RS) imagery.

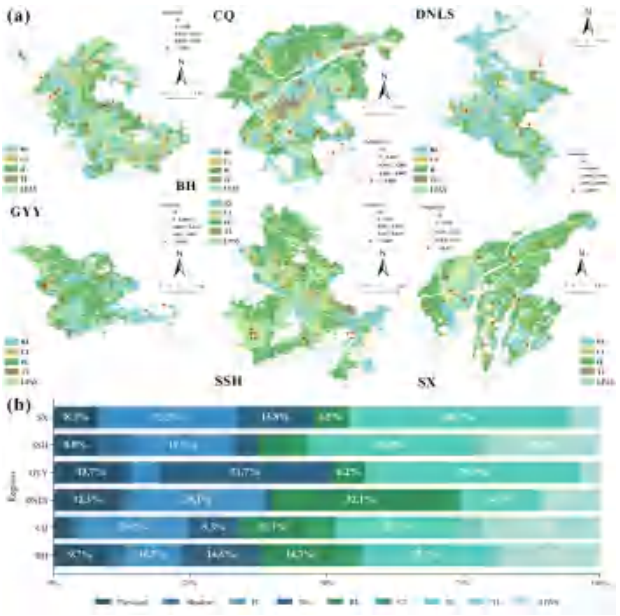



Fig. Occlusion sensitivity analysis (OSA) unveils critical scenarios driving Cd pollution prediction. (a) Spatial distribution of high-sensitivity patches overlaid on urban land use types. (b) Quantitative contribution of different land use types to positive sensitivity, unequivocally identifying industrial land (IL) as the primary driver across regions. RL—residential land; CL—commercial land; IL—industrial land; TL—transportation land; LPAS—land for public administration and service; FL—forest land; WA—water area.

Our methodology establishes a novel link between extensive ground-truth data (14,058 soil samples) and high-resolution RS imagery in Dongguan, China. We designed a lightweight convolutional neural network, SI-LICNet, specifically architected to preserve large-scale spatial information essential for identifying landscape-level pollution indicators. Crucially, to deconstruct the model's decision-making process, we employed Occlusion Sensitivity Analysis (OSA) to quantitatively identify and visualize the critical scenarios most influential in predicting Cd pollution.

The SI-LICNet models demonstrated robust predictive performance, achieving regional Area Under the Curve (AUC) values ranging from 0.747 to 0.905 and recall rates consistently exceeding 70%, confirming their efficacy in detecting pollution hotspots. The OSA results provided direct, interpretable evidence: industrial land was unequivocally identified as the primary landscape type driving high-Cd predictions across functionally diverse urban regions. For instance, in regions like Binhai (BH) and Gongyeyuan (GYY), industrial zones and adjacent transportation networks showed the highest sensitivity. Interestingly, even misclassified "false positive" samples were found to represent areas with high contamination risk, as their landscape features closely mirrored those of verifiably polluted sites.

This work transforms deep learning from a "black-box" classifier into an interpretable tool for environmental forensics. By successfully identifying key pollution-related scenarios from satellite imagery, our approach offers a scalable, cost-effective, and scientifically rigorous methodology for dynamic soil pollution monitoring and targeted environmental management.

# Advancing Corn Yield Prediction through Cross-Scale Integration Approaches

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**ABSTRACT**

Predicting crop yields consistently from field to regional scales is still a major limitation in precision agriculture, especially due to the difficulty of linking in situ observations with remotely sensed data. In this work, we introduce a new multi-scale modeling approach that combines ground-truth measurements, UAV imagery, and satellite products to improve the reliability of corn yield estimates. The study was carried out at a farm in Ontario, Canada, using Sentinel-2 imagery together with fine-resolution UAV data acquired over the 2019 and 2020 growing seasons. Two yield estimation frameworks were implemented and evaluated: a traditional satellite-only model and a novel multi-scale upscaling scheme that explicitly links information across spatial resolutions. The upscaling framework outperformed the conventional approach, increasing the correlation coefficient from 0.82 to 0.88. More importantly, the proposed upscaling approach markedly lowered prediction uncertainty, reducing the proportion of high-uncertainty areas (>1%) from 43.3% to 20.4%. Examination of spectral predictors highlighted clear scale-specific responses, as vegetation indices including the canopy chlorophyll content index (CCCI), chlorophyll index (CIgreen), and green normalized difference vegetation index (GNDVI), exhibited different levels of influence depending on spatial resolution. In addition, the framework enabled explicit tracking of uncertainty transfer across scales, addressing a key limitation of existing precision agriculture methodologies. The results confirm that structured integration of observations from multiple spatial scales can simultaneously enhance yield prediction accuracy and minimize uncertainty, with direct relevance for precision agriculture and sustainable crop management practices.

**Keywords:** Yield prediction; Machine learning; Satellite imagery; Upscaling; Precision agriculture

# Enhancing Precision Nitrogen Management through Integration of Soil Properties and Remote Sensing

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**ABSTRACT**

Sustainable crop production increasingly relies on maximizing nitrogen (N) efficiency while safeguarding yield levels. Nevertheless, the intertwined effects of soil variability, fertilizer management, and plant physiological response complicate the development of accurate, site-specific N recommendations. This research therefore sought to (a) determine how soil characteristics influence crop spectral reactions to N supply, and (b) derive soil-dependent N response models using remote sensing metrics. A comprehensive dataset combining soil attributes, nitrogen application levels (zero, regular, and luxury rates), and Sentinel-2–based spectral metrics was collected from a maize field in Ontario, Canada. Structural equation modeling and random forest techniques were applied to derive soil-dependent N response relationships and to assess predictive performance under three progressively integrated modeling scenarios. Soil cation exchange capacity (CEC) and organic matter (OM) emerged as key regulators of N responsiveness, with the green normalized difference vegetation index (GNDVI) exhibiting the strongest association with yield ($r = 0.80$) in areas characterized by high CEC. Including soil information increased yield prediction accuracy by 16% relative to models relying solely on remote sensing, while the additional integration of N management variables further decreased prediction error by 21%. Although applying N at luxury rates resulted in a 4.8% yield increase over recommended levels, the magnitude of this gain differed markedly across soil conditions. These findings demonstrate that soil heterogeneity plays a central role in governing crop responses to N inputs, underscoring the limitations of uniform fertilizer recommendations. The proposed framework supports the development of soil-specific N management strategies that can improve yield outcomes while advancing environmental sustainability in heterogeneous agricultural landscapes.

**Keywords:** Soil properties; Yield; Nitrogen management; Structural equation modeling; Data integration; Machine learning

# Geospatial Index of Acid Mine Drainage (IIMSDAM) Impact on Soils

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**ABSTRACT**

Mining activity has driven technological and economic development but also generates severe environmental impacts, such as Acid Mine Drainage (AMD). AMD occurs when sulfides react with water, oxygen, and microorganisms, producing acidic solutions that mobilizes potentially toxic elements (PTEs). AMD contaminates soil, as well as surface and groundwater bodies, deteriorating their quality, affecting ecosystem services, and posing risks to human health.

Traditionally, AMD evaluation has relied on single chemical analysis of parameters like pH and electrical conductivity (EC), as well as on the identification of secondary minerals (e.g., jarosite, anhydrite, goethite). However, there is no integrated index based on Geographic Information Systems (GIS), geostatistics, and remote perception (RP) combining these parameters to estimate the impact of AMD on soils.

A mixed RS, geostatistics and GIS approach, offers an efficient and low-cost alternative to identify and spatially model AMD affected edaphic parameters (geochemical and mineralogical). Thus, our research proposes the AMD Soil Impact Index (herein called "IIMSDAM") applicable to any area presenting historical or active mining operations. The developed index parameters are pH, EC, slope, distance to AMD sources (mines and mine tailings), and secondary AMD minerals (Jarosite, goethite, ferrhidrita, anhydrite, gypsum).

The AMD index was applied to the municipalities of Banámichi, Huépac, and San Felipe de Jesús, Sonora, Mexico, a region with a long mining history and potential AMD contamination.

The approach we have adopted allowed AMD affected soil mapping and classification, representing a valuable resource to optimize decision-making in environmental management and mining exploitation. Our study provides a globally replicable tool for the prevention, monitoring, and remediation of mining-degraded soils.

**Keywords:** Acid Mine Drainage, Soil, Remote Sensing, Mapping, Environment,GIS

# Multi-view hyperspectral feature can improve soil property retrieval

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**ABSTRACT**

Hyperspectral remote sensing has been increasingly used for retrieving soil properties. Most previous studies have relied on reflectance data acquired from a single viewing angle, typically the nadir direction, while the potential benefits of multi-view hyperspectral observations remain insufficiently explored. This study aims to develop an optimal framework for soil property retrieval by incorporating soil bidirectional reflectance distribution function (BRDF) characteristics and to identify the multi-angle hyperspectral features that enhance retrieval accuracy. Soil reflectance was measured at 48 viewing angles for different soil samples. Three feature wavelength selection methods and four modeling algorithms were evaluated to identify the most effective combinations for retrieving soil organic matter content, cation exchange capacity, pH, and sand, silt, and clay contents using hyperspectral data from different viewing angles. Variations in retrieval accuracy and selected feature wavelengths across view angles were further analyzed to determine the key multi-angle spectral features contributing to improved predictions. Finally, these multi-angle spectral features were simulated from nadir reflectance and validated for their effectiveness. The results showed that, for linear models, the combined feature selection strategy using random frog (RFROG) and competitive adaptive reweighted sampling (CARS) outperformed either method alone, with $R^2$ increases of 3.1%–197% and 2.3%–214%, respectively. When nonlinear models were applied, the RFROG–CARS combination still achieved stable performance across different soil properties. Overall, nonlinear algorithms generally yielded lower retrieval accuracy than linear models, with $R^2$ decreasing by 33%–86%. Retrieval accuracy based on multi-view reflectance was consistently higher than that obtained from any single viewing angle. When using single-angle reflectance, retrieval performance varied substantially with view angle. The multi-angle hyperspectral features that improved soil property retrieval were jointly influenced by wavelength and viewing geometry. Near-infrared wavelengths were selected more frequently than visible wavelengths. Although selected feature wavelengths originated from most of the 48 view angles, their relative contributions varied among angles and depended on the specific soil property. Overall, acquiring soil bidirectional reflectance from multiple view angles is preferable for improving soil property retrieval accuracy. Retrieval results based on simulated multi-angle reflectance showed clear improvements compared to those using reflectance from a single view angle. Relative to nadir observations (5°) and the single view angle with the best performance, $R^2$ increased by 17%–42% and 3.7%–8.4%, respectively, across different soil properties. These findings provide valuable insights for enhancing soil property retrieval accuracy using multi-angle hyperspectral observations.

# Physically supervised harmonic framework for spatial characterization of apparent soil thermal diffusivity between 5 and 10 cm.

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**ABSTRACT**

Soil thermal diffusivity (KT) controls the attenuation and phase shift of the thermal wave within the soil profile. At the annual scale, KT can be estimated from temperature time series at two depths under the assumption of one dimensional heat conduction (1D) [ 1,2]. The aim of this study was to develop and apply a spatial estimation framework for apparent thermal diffusivity between 5 and 10 cm that combines a statistical harmonic fit supervised by an explicit physical coherence control between depths. Uruguay has daily soil temperature maps at 5 and 10 cm depth estimated from in situ observations and satellite imagery [3]. From these maps, intra annual pixel wise time series were built and the first annual harmonic was fitted by least squares. From these estimates, two diffusivity estimators were derived, one from logarithmic amplitude attenuation and one from the interdepth phase lag. Internal consistency metrics were defined to quantify the mismatch between attenuation and phase lag, as well as a symmetric relative discrepancy between the two estimates. To define global tolerance thresholds, a Monte Carlo procedure was implemented using bootstrap resampling with replacement of paired daily residuals from in situ temperature series, preserving the joint dependence between depths and filtering physically feasible realizations. Under the assumptions of the 1D model, a physical coherence domain (Dphys) was defined for the vector of harmonic parameters by imposing amplitude and phase constraints. The fitted harmonic series are supervised by verifying membership in Dphys and internal consistency relative to the defined thresholds. Local intra annual flags were defined based on vertical temperature differences and residuals relative to the harmonic fit. For series showing locally incompatible behavior, a subset based temporal filtering was applied, which minimizes the exclusion of observations and seeks to recover solutions within Dphys without modifying the data or forcing the observed signal, allowing the time series to express their intrinsic variability within a coherent domain. The presentation will discuss the performance of the physical control and the quality assurance framework in generating annual and typical apparent diffusivity products and their independent validation.

**Acknowledgments**

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# A Meta Learning Framework for Spatio-temporal Mapping of Cropland Topsoil pH in Southern China

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**ABSTRACT**

Understanding the spatio-temporal patterns of soil pH is critical for mitigating cropland soil acidification in southern China. However, croplands in this region are highly fragmented, geomorphological conditions are complex, and most existing regional digital soil mapping approaches exhibit poor spatiotemporal generalization capability. This study aims to develop a robust modeling framework with strong generalization performance for predicting cropland topsoil (0–20 cm) pH in southern China.

Multi-temporal soil survey datasets (1980–2015; n = 20,484) were integrated with corresponding temporal and geographic information, together with 135 static and dynamic environmental covariates. These covariates primarily included 30 m resolution topographic variables, 30 m remote sensing indicators, as well as climate, fertilization, and atmospheric nitrogen deposition variables. The dataset was randomly divided into a training set (70%) and a testing set (30%).

Meta-tasks were constructed by dividing the study area into six geomorphic units (plain, platform, hill, low mountain, mid-mountain, high mountain), with each unit as an independent meta-task for soil pH prediction. A double-loop optimization framework based on Model-Agnostic Meta-Learning (MAML) was employed: in the meta-training stage, the shared feature extractor and meta-network were iteratively optimized to obtain a universal initial parameter set generalizable across geomorphic partitions; in the meta-update stage, these initial parameters were rapidly fine-tuned for each geomorphic meta-task using small-scale samples. This process ultimately produced a globally optimized feature extractor and parameter set applicable to all geomorphic meta-tasks. The predictive framework adopted an ensemble learning strategy integrating four base learners: Partial Least Squares Regression (PLSR), Support Vector Regression (SVR), Random Forest (RF), and Multi-Layer Perceptron (MLP).

The proposed framework significantly outperformed conventional ensemble learning approaches, increasing $R^2$ by 38.49% and reducing RMSE by 6.24%. The pH distribution maps generated by the framework clearly illustrate the pronounced regional acidification over the past four decades. This study provides a high-accuracy framework for long-term regional-scale monitoring and mapping of soil pH, offering valuable scientific support for region-specific soil management and sustainable cropland utilization.

**Acknowledgments**

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# Differentiating parent materials using the soil thermal gradient between 5 and 10 cm at national scale (Uruguay)

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**ABSTRACT**

Soil temperature spatiotemporal variability is controlled by physical factors influenced by parent material. The soil effective thermal properties and the variations in the soil atmosphere energy balance are modulated by mineralogy, structure, the relative water air content, and geomorphology [1,2]. In this study, we evaluated the potential of the soil thermal gradient (G5,10) as a statistically valid indicator to differentiate parent materials across Uruguay, using the national 1:500,000 Geological Map [3] as the References framework. Using monthly soil temperature maps at 5 and 10 cm for 2001 to 2021, previously developed and validated [4], G5,10 was computed and its distribution was compared among all mapped geological units (n = 53). For each month, G5,10 values were grouped by unit and the Kruskal Wallis test was applied, followed by Dunn post hoc comparisons with Bonferroni correction. In addition, the annual thermal singularity of each unit was quantified as the number of significant differences accumulated across the 12 months. Median G5,10 differed among units in all months ($p < 0.0001$). Discrimination strength showed seasonal variability: the number of significant pairs reached a maximum in February (n = 170) and a minimum in November (n = 44). Among parent materials, Cenozoic sedimentary units (unconsolidated coastal and fluvial sediments) and Mesozoic basaltic units showed the highest annual dissimilarity, differing from 42 and 40 units, respectively. In addition, 83% of the units (44 of 53) differed from at least one neighboring unit, indicating sensitivity to contacts. These results support G5,10 as a spatially explicit thermal indicator sensitive to contacts between parent materials, with potential to prioritize areas for verification and boundary refinement using higher resolution surveys.

**Acknowledgments**

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# Mapping Soil Salinity with Satellite Embeddings and Environmental Covariates

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**ABSTRACT**

Soil salinization is one of the most widespread and rapidly intensifying forms of land degradation, posing a critical threat to food security and ecosystem resilience. Despite extensive in-situ soil salinity measurements through national and global soil databases, spatially consistent and generalizable soil salinity mapping remains constrained by the limited representational capacity of traditional remote sensing features and their sensitivity to regional, temporal, and management variability. Spectral bands and handcrafted indices often require site-specific calibration and show reduced transferability across landscapes and years.

In this study, we present a soil salinity mapping framework that integrates satellite embeddings from the Google Satellite Embedding V1 Annual dataset with environmental covariates to predict electrical conductivity of the soil saturation extract (ECe) across heterogeneous land covers. The annual 10 m satellite embeddings provide a harmonized, multi-sensor representation of land surface conditions, while environmental covariates capture soil-forming factors and hydroclimatic controls on salinization processes. Using field ECe measurements, we train machine learning regression models to link embedding–covariate feature space with observed soil salinity and evaluate performance across regions and years.

Results show that the combined embedding and covariate approach improves predictive robustness and cross-region generalization compared with models relying solely on spectral features and environmental covariates. The embedding-based representation reduces dependence on manual feature engineering and mitigates inconsistencies arising from sensor differences and temporal variability. This work demonstrates how foundation model-derived satellite embeddings, when coupled with environmental context, enable scalable and transferable soil salinity mapping, supporting precision agriculture, land management, and long-term soil health monitoring.

**Acknowledgments**

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# Spatiotemporal Dynamics and Uncertainty Attribution of 1 km Satellite Soil Moisture Products Across China: A Comparative Assessment via TCH and OPGD

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**ABSTRACT**

Soil moisture (SM) serves as a critical nexus linking terrestrial water, energy, and carbon cycles. However, while 1 km high-resolution products have overcome the spatial constraints of traditional microwave sensors, their performance consistency and error structures across China's complex underlying surfaces remain poorly characterized. To bridge this knowledge gap, this study established a comprehensive evaluation framework by integrating spatiotemporal pattern analysis, Three-Cornered Hat (TCH) uncertainty quantification, and Optimized Parameter Geodetector (OPGD) modeling. We systematically assessed four representative 1 km products—Gap-filled ESA-CCI, SPL2 SMAP, SMCI 1.0, and GSSM1KM—over the period 2003–2020.

Our results demonstrate a pervasive, subtle declining trend in SM across all datasets, marked by significant seasonal periodicity and synchronized interannual fluctuations during 2008 and 2011. Spatially, although a consistent southeast-to-northwest SM gradient is observed, substantial discrepancies emerge in topographically heterogeneous and transition zones. Crucially, TCH analysis reveals a distinct spatial hierarchy of reliability, where SMCI 1.0 exhibits the highest stability (lowest relative uncertainty), whereas SPL2 SMAP shows the greatest uncertainty in complex landscapes. Attribution analysis via OPGD further identifies that annual mean precipitation (AMP) and its interaction with temperature (AMP×AMT) are the primary determinants of uncertainty for most products. In contrast, SPL2 uncertainty is uniquely driven by the interaction between vegetation canopy (LAI) and temperature. Ultimately, these findings clarify the regional applicability of high-resolution SM datasets, providing a vital scientific baseline for product selection and the optimization of retrieval algorithms in climatically diverse regions.

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# A Property-Dependent Strategy for Digital Soil Mapping: Optimizing Sentinel-2 Time-Series for Stable and Dynamic Soil Attributes

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**ABSTRACT**

Digital soil mapping (DSM) often relies on a «one-size-fits-all» approach to remote sensing data processing, applying uniform mosaicking or scene selection techniques regardless of the physical nature of the target soil property. This study, conducted across a 2703-hectare area of the dry Eurasian steppe (Volgograd region), challenges this paradigm by proposing a property-dependent strategy that tailors data processing to the temporal stability of soil attributes.

Using 131 soil samples collected in the summer of 2019 and the Sentinel-2 archive processed via Google Earth Engine, we compared two primary processing groups: (1) per-pixel temporal compositing (6 scenarios) and (2) per-date scene selection (2 scenarios). Our results reveal a clear methodological dichotomy. Stable soil properties, specifically soil texture, are best predicted using per-pixel temporal compositing, which acts as a temporal filter to minimize spectral noise from transient surface conditions ($R^2$ up to 0.56 for sand and 0.51 for silt). In contrast, dynamic properties, particularly soil moisture, benefit from per-date scene selection that captures a coherent «physical snapshot» of the landscape ($R^2$ = 0.41 for moisture using the driest-scene approach).

Furthermore, we integrated physical geomorphometry (PG) variables, representing the energetic potential of the landscape and legacy soil data as covariates. Variable importance analysis demonstrated that while legacy data provides a critical pedogenetic baseline for zonal Kastanozems and Solonetz complexes, PG variables (e.g., Index of Slope Energy Disequilibrium) are vital for predicting structurally dependent properties like soil erodibility (K-factor) and bulk density. We synthesize these findings into a «Process-Property-Strategy Framework» offering a dual-component solution for precision agriculture: a «Strategic Base Map» for long-term planning (stable properties) and a «Tactical Monitoring Layer» for in-season management (dynamic properties). This research provides a robust methodological foundation for the next generation of property-specific DSM services.

**Keywords:** Digital Soil Mapping, Property-Dependent Strategy, Physical Geomorphometry, Soil Moisture, Soil Texture.

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# Innovation in Large-scale Soil Pollution Investigation Driven by Multi-source Data: A Transition from Grid-based to Precision-based Approaches

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## ABSTRACT

Soil pollution, characterized by its cumulative nature, heterogeneity, and invisibility, poses a significant challenge to the sustainable utilization of global land resources. Traditional large-scale investigation methods often suffer from inadequate spatial representation and insufficient reliability in trend assessments, making it difficult to meet the demands for precise soil environmental risk management. To address these issues, this study proposes a precision-based investigation technical framework that integrates multi-source data with spatial differentiation statistics, the core framework of which covers five links: "pollution impact range identification—spatial unit partitioning—differentiated investigation—trend prediction—classified control", aiming to achieve a transition from grid-based investigation to precision-based investigation. The technical system first utilizes knowledge graphs and machine learning methods to integrate pollution source inventories, land use, and historical monitoring data to construct an evaluation matrix of "pollutant toxicity—emission intensity—migration capacity," quantifying the impact range of industrial point sources and agricultural non-point sources. Secondly, based on the principles of spatial differentiation statistics, homogeneous investigation units are partitioned by combining environmental factors and land use characteristics to achieve refined zoning for types such as agricultural and construction land, and a spatial sampling optimization model is applied to generate cost-controlled sampling schemes. In the trend prediction link, panel data is integrated with long-term observation information, and policy and flux analyses are coupled to construct a comprehensive soil pollution change prediction model, improving the reliability of trend assessments. Finally, the pollution status of each land use patch is presented intuitively through a "Red-Yellow-Green" map, aligning with ecological environment partitioning and spatial planning requirements to support classified and hierarchical management. Application results demonstrate that this technical framework can significantly improve the accuracy of source-sink relationship analysis and investigation efficiency, providing an innovative technical path for global large-scale soil pollution investigation and contributing to the goal of "comprehensive soil environmental risk management" for a beautiful China.

**Keywords:** Soil pollution; Large-scale investigation; Source-sink relationship; Investigation unit; Classified and hierarchical management

# The spatiotemporal variation in soil inorganic carbon

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**ABSTRACT**

Widespread soil acidification due to atmospheric acid deposition and agricultural fertilization can significantly accelerate soil carbonate dissolution and CO2 release. Here, we collected nationwide and global soil datasets and developed machine learning and process-based models to quantify the spatiotemporal changes in soil inorganic carbon (SIC) stocks. Three conclusions were achieved as follows. (1) We observe an overall decrease in SIC stocks in topsoil (0–30 cm) (11.33 g C m–2 yr–1) across China's cropland, forest and grassland from the 1980s to the 2010s. Total SIC stocks have decreased by~ 8.99±2.24% (1.37±0.37 Pg C) (Song et al., 2022). (2) Global soils store 2305 ± 636 (±1 SD) Pg C as SIC over the top 2-meter depth. Machine learning-based models identify that soil pH acts as the most important predictor for the variation in SIC (29%). Under future scenarios, soil acidification associated with nitrogen additions to terrestrial ecosystems will reduce global SIC (0.3 meters) up to 23 Pg SIC over the next 30 years, with India and China being the most affected (Huang et al., 2024). (3) Finally, we develop a new process-based Soil Inorganic Carbon Turnover Model (SINCOM) to quantify the impacts of climate change on SIC dynamics from 2015 to 2100 across China. SINCOM integrates a physically-based soil water balance module with a carbonate geochemical equilibrium, excluding acidification processes to isolate climate-driven effects on SIC. We find a decrease of 209–225 Tg C in SIC stock in 0–2 m soils under four Shared Socioeconomic Pathways, with higher loss rate in humid regions (281–960 mg C m-2 yr-1) than those in arid regions (6–29 mg C m-2 yr-1).

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# A Zonal Optimization Mapping Framework for Soil Taxonomic Classification in Large Flat Regions: A Case Study of the Songnen Plain

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**ABSTRACT**

Currently, generating quantitative Soil Taxonomic Classification maps from legacy Soil Genetic Classification maps relies primarily on direct taxonomic correlation. However, this method often yields substantial mapping errors, especially in large, flat regions with weak environmental gradients. To address this, we propose an innovative framework of "first directly correlating the legacy soil map to extract pseudo points, followed by zonal optimization." This framework was validated in China's Songnen Plain, one of the most challenging large flat terrains, with the aim of providing a new solution for developing high-quality localized Soil Taxonomic Classification maps. Initially, a 1:1,000,000 Soil Genetic Classification map was directly correlated to produce a map of Chinese Soil Taxonomy (CST) , achieving an initial accuracy of only 44%. Subsequently, a digital soil mapping approach based on hierarchical zoning was implemented. This involved partitioning the area according to a hierarchical framework, extracting pseudo points within each zone, integrating multi-source environmental covariates, and finally performing spatial prediction of soil classes using a multi-level random forest model. The results demonstrate that the zonally optimized map achieved an overall accuracy of 53%, significantly outperforming both the direct correlation result and a conventional whole-area modeling approach (which yielded an accuracy of only 25%). This confirms the effectiveness of the proposed framework for achieving high-accuracy soil type mapping in flat regions. Our study provides a referable technical pathway for the cost-effective and robust updating of soil maps in large, flat regions worldwide.

# Future Projections of Global Belowground Net Primary Productivity in Response to Climate Change

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**ABSTRACT**

Belowground Net Primary Productivity (BNPP) refers to the net photosynthetic products allocated by plants to the belowground parts through their root systems, serving as a crucial factor influencing the accumulation and stability of soil organic carbon. Under global climate change, BNPP exhibits high sensitivity to the global carbon cycle and ecosystem adaptive capacity, making its accurate quantification scientifically important for understanding ecosystem functions and developing effective climate change strategies. However, existing model-based assessments of environmental factors contributions to BNPP remain limited, and quantitative analyses of BNPP trends under different climate scenarios are still lacking. This study integrates global BNPP observational data with multi-source datasets, including climate, soil, and topographic variables. We employed XGBoost Residual Kriging (XGBRK) to simulate the spatial distribution of BNPP at 0–2 m depth. SHapley Additive exPlanations (SHAP) analysis was applied to evaluate the influence of different environmental variables on BNPP. In addition, Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model data were utilized to project future BNPP dynamics under different emission scenarios. The results indicate that: (1) the global mean BNPP is 1.782 $Mg \cdot ha^{-1} \cdot yr^{-1}$ witn tropical forests (2.501 $Mg \cdot ha^{-1} \cdot yr^{-1}$) and warm temperate forests (2.585 $Mg \cdot ha^{-1} \cdot yr^{-1}$) exhibiting the highest BNPP values, whereas tundra ecosystems show the lowest (0.724 $Mg \cdot ha^{-1} \cdot yr^{-1}$); (2) Among the environmental factors, climate variables are the primary drivers of BNPP (SHAP: 59.5%), followed by soil properties (24.6%), with topographic variables contributing the least (15.9%), and significant differences were evident among various biomes; (3) In the future (2081-2100), global BNPP shows an overall increasing trend (~0.05 $Mg \cdot ha^{-1} \cdot yr^{-1}$), which is particularly pronounced under the high-emission scenario (SSP5-8.5), while warm temperate forests are the only biome exhibiting a productivity decline. Our findings confirmed that climate is the dominant factor influencing BNPP spatial distribution, followed by soil properties, while topography has a relatively minor effect. Although the future spatial pattern of BNPP remains broadly consistent with the current distribution, intensifying emission scenarios may drive some biomes toward their ecological adaptation thresholds, thereby weakening the differences among biomes.

# A Multi-Source Product Assessment and Uncertainty-Aware Modeling Framework for SOC Mapping in China

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**ABSTRACT**

Soil Organic Carbon (SOC) is pivotal for terrestrial carbon cycle research, yet the reliability of current products is often compromised by discrepancies in data sources and mapping methods. To address spatial uncertainty hindering decision-making, this study developed a comprehensive framework coupling robust validation with explainable modeling to optimize SOC mapping in China. The study involved two phases. First, four mainstream products—HWSD V2.0, SoilGrids 250m V2.0, CSDL V2.0, and the China High-Resolution Grid—were evaluated using benchmarks from the 2nd National Soil Census and the Soil Series of China. The Three-Cornered Hat (TCH) method was applied to quantify relative error variances independent of ground truth. Second, guided by a bibliometric review, eight algorithms (e.g., SVM, XGBoost, QRF, RFRK) were compared via 10-fold cross-validation to assess prediction accuracy (RMSE) and uncertainty validity (PICP), while SHAP (SHapley Additive exPlanations) analysis was used to identify environmental drivers. Results indicate that product suitability varies spatially across different landscapes, while TCH analysis confirmed that relative noise distribution is significantly modulated by topographic heterogeneity, with higher uncertainty in hilly regions. Regarding modeling, Random Forest Regression Kriging (RFRK) yielded the highest prediction accuracy, whereas Quantile Regression Forests (QRF) offered the most reliable uncertainty quantification. Furthermore, SHAP analysis identified Mean Annual Precipitation (MAP) and other key factors as dominant drivers, crucially revealing that interpretation reliability decreases in complex terrains. Ultimately, this framework enhances the transparency and accuracy of SOC mapping, providing the reliable data foundation necessary for delivering effective global soil services and solutions.

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# Innovative Technologies for European and Global Soil Services and Solutions - SoilWise Project Achievements

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## ABSTRACT

Soil data and knowledge, despite its critical role in sustainable land management and environmental stewardship, has long been hindered by significant obstacles in terms of accessibility, interoperability, and reusability. From the perspective of the FAIR (Findable, Accessible, Interoperable, and Reusable) principles, many soil datasets remain siloed, difficult to discover, and challenging to integrate across different platforms and research contexts. These challenges have limited the broader potential for informed decision-making and cross-disciplinary collaboration in soil science.

The SoilWise project directly addresses these obstacles by democratizing access to digital soil data including knowledge through innovative technologies and a user-centric platform. By aggregating metadata from more than a dozen leading open repositories, including Zenodo and OpenAire, SoilWise has successfully harvested over 30,000 metadata assets that span from local soil mapping campaigns to global soil data, all available through the SoilWise catalogue. This vast repository helps overcome the "findability" and "accessibility" barriers by centralizing and standardizing soil data in an open-access framework.

A key achievement of the project is the identification and resolution of data duplicities, which enhances data quality and interoperability, ensuring that users can trust the datasets they access and apply them across varied contexts. To further support the FAIR principles, the project has developed comprehensive guidelines and strategies for ensuring that soil data is both reusable and reusable at scale. These include the use of standardized metadata, persistent identifiers, and clear data documentation, as well as the adoption of shared vocabularies and ontologies to facilitate seamless data integration.

To improve user experience and broaden adoption, SoilWise has also integrated a ‘Soil Companion’ chatbot, offering real-time guidance, and developed clear guidelines that help users navigate the platform and make the most of the data available. By promoting a holistic and FAIR-compliant approach to soil data management, SoilWise fosters a more collaborative and data-driven approach to soil science, enabling researchers, policymakers, and land practitioners to make better-informed decisions for sustainable land use and soil management. This presentation will explore these achievements, illustrating how SoilWise is advancing the democratization of soil data on a global scale.

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# Predicting Textural Classes Using GPR-derived Geophysical Data and Optimized Machine Learning in Subtropical Forests

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## ABSTRACT

Soil texture should be obtained at a useful scale for sustainable agricultural energy and food systems in colluvium-alluvial plains. Ground Penetrating Radar (GPR) can collect data in a non-destructive and rapid manner to assist in soil texture prediction. In this study, the objective was to evaluate the effect of geophysical data such as electromagnetic wave time (EMWT), electromagnetic wave amplitude (EMWA), and dielectric constant (K) extracted from GPR profiles on predicting clay and sand contents. We also explored the impact of use and non-use gravimetric water content (GWC) as a predictor covariate. The use of variable selection tools in machine learning (ML) algorithms was evaluated, and the nested holdout by GPR profile method was optimized for training and selecting suitable models for prediction. Soil samples were collected at 59 soil cores at 0.20 m intervals up to a depth of 1 m (total 5 layers), along with a hand auger to assess the variation textural and GWC. Data from GPR profiles were extracted for each soil core in the 5 layers to relate them to soil texture data and GWC. Morphometric parameters were obtained from a Digital Terrain Model (pixel size 5 m). ML algorithms including Cubist, Random Forest (RF), Support Vector Machine (SVM), and a Linear Model (LM) were compared. Results were trained and validated using an optimized nested holdout test by GPR profile. Covariate modeling with selection by near-zero variance, correction removal, and importance removal was necessary for model parsimony, with covariates related to sedimentological processes. The covariate with 100% importance in predicting clay and sand contents was GWC for the Cubist, RF, and SVM models. 'Depth' as a covariate showed a mean relative importance ≥ 75% for the prediction of clay, and > 50% for sand content in the Cubist and RF models, indicating a higher sand contribution in deeper layers. The covariates extracted from the GPR profiles, EMWT figure in the top 10 main predictors of clay content for the Cubist, RF, and LM models. Sand content was an important predictor in the RF and LM models. EMWT reduces the subset of covariates in the models and improves predictive performance. Soil texture predominantly presented a clay textural class, which interfered with the lower importance of EMWA and K covariates. The models with the best performance were Cubist and RF for predicting clay (LCCC 0.432 and 0.410, respectively) and sand content (LCCC 0.505 and 0.506, respectively), differing only in $R^2$ according to the Kruskal-Wallis test. Clay and sand contents in sedimentary environments were efficiently modeled using optimized ML techniques and a dataset combining morphometric, electromagnetic, and GWC data across depths. Future studies should further explore the application, particularly of EMWT, as a covariate in ML models. Our approach provides a more efficient and optimized method for texture prediction in sedimentary environments in subtropical forests.

# Integrating Proximal and Remote Sensing to Cross-scale Quantify Soil Organic Carbon and Moisture Dynamics via Multi-model Learning

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**ABSTRACT**

Soil organic carbon (SOC) and soil moisture (SM) are fundamental variables for soil health and ecosystem functioning. However, consistent quantification of their spatial patterns and temporal dynamics from local to global scales remains challenging due to scale mismatches, sensor heterogeneity, and complex soil–environment interactions. Bridging proximal and remote sensing is essential for scalable and physically meaningful soil monitoring. Here, this study presents a cross-scale framework that integrates proximal soil sensing (i.e., SOC spectroscopy libraries, field time-domain reflectometry and cosmic-ray SM sensors), airborne-satellite remote sensing, and process-based soil-vegetation-atmosphere radiative transfer models to quantify surface SOC and SM dynamics from local to regional or global extents. Proximal optical spectroscopy and SM sensors capture soil organic carbon and moisture-related signals accurately, while satellite remote sensing provides broader scale signals on surface SOC and SM across diverse conditions. These complementary data streams are fused using a multi-model learning approach that combines data-driven machine learning and process-based models via knowledge-guided machine learning. Results show that explicitly integrating proximal and remote sensing reduces domain gaps, improves cross-scale generalization, and enhances the estimation of SOC and SM across heterogeneous landscapes. The proposed framework advances scalable soil monitoring and supports applications in regional or global soil assessment, land management, and Earth system science.

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# Warming and Drying Patterns across Iran: A Three-Decade Remote Sensing Perspective on Land Surface Temperature, Soil Moisture, and Vegetation Dynamics

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## ABSTRACT

Understanding the relationship between land surface temperature (LST), soil moisture (SM), and vegetation (V) is crucial for evaluating the impacts of climate change in arid and semi-arid regions. Iran, a country predominantly characterized by such climates, presents a critical case study. Its complex topography, featuring the high-altitude Alborz and Zagros Mountain ranges, the vast central deserts (e.g., Dasht-e Kavir and Dasht-e Lut), and narrow coastal plains along the Caspian Sea and Persian Gulf, creates sharp climatic gradients. This results in a spectrum from hyper-arid to humid subtropical zones, making its ecosystems highly sensitive to hydro-climatic fluctuations.

This study provides a large-scale spatiotemporal analysis of LST, surface soil moisture (SSM), and vegetation dynamics across this topographically and climatically diverse nation over a 30-year period (1995–2025) using satellite remote sensing data. Multi-temporal Landsat (5 TM, 7 ETM+, 8 OLI/TIRS, and 9 OLI-2/TIRS-2) imageries were processed in the Google Earth Engine (GEE) cloud-computing platform to derive annual cloud-free LST composites and vegetation indices (NDVI, SAVI). SSM was estimated using the OPTRAM (Optical Trapezoid Model), a physically-based method that leverages the empirical relationship between shortwave infrared transformation, vegetation index, and soil moisture within the LST-vegetation index feature space. Temporal trend analyses, including the Mann-Kendall and Sen's slope estimators, were applied to investigate long-term changes in LST, SSM, and VIs. Spatial analyses, including correlation and hot-spot analysis (Getis-Ord Gi*), were conducted to examine their co-variability across Iran's distinct climatic regions. Furthermore, relative change metrics were calculated to identify areas experiencing notable shifts in soil moisture conditions and associated vegetation response over time.

The results indicate significant spatial and temporal variability in LST, SSM, and vegetation across the study area. Notably, the arid interior basins and semi-arid northwestern regions show concurrent and statistically significant warming trends, SM decline, and V stress. In contrast, some northern and highland areas exhibit more stable or complex patterns. The generated maps provide an integrated overview of potential climate-related SM and V dynamics and identify regions, particularly in central, eastern, and southwestern Iran, that appear more sensitive to long-term environmental change and land degradation. This study demonstrates the value of combining long-term satellite observations, RS–based SM models like OPTRAM, and vegetation indicators within an integrated analytical framework (e.g., GEE) for national-scale assessments of soil–climate–vegetation interactions. The findings offer an empirical basis for targeted climate adaptation and land management strategies in vulnerable arid regions.

**Keywords:** Climate Change, Land Surface Temperature, Soil Moisture, Remote Sensing, Google earth engine

# SOCBIO-MAP: Integrating Earth Observation, AI, and In-Situ Sampling to Democratize High-Resolution Soil Organic Carbon and Biodiversity Mapping

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**ABSTRACT**

Reliable and accessible soil information is essential for sustainable land management, yet existing digital soil mapping (DSM) approaches often rely on sparse ground data, high sampling costs, and limited usability for non-technical stakeholders. This creates substantial uncertainty in estimating soil organic carbon (SOC) stocks, soil biodiversity, and related ecosystem functions. SOCBIO-MAP addresses these challenges by combining Earth observation (EO), AI-based modelling and optimized in-situ sampling to deliver scalable, cost-efficient and transparent soil information services. The approach responds directly to global needs identified in current DSM discourse, including the integration of multisource data, increased resolution, and democratized access to soil intelligence.

SOCBIO-MAP fuses predictors from various EO sensors (including multi-spectral and SAR) with DEM's and targeted soil sampling guided by EO-driven optimization. This workflow aims to minimize field sampling numbers while maintaining model accuracy, enabling reliable SOC stock estimation across heterogeneous landscapes in Chile and Paraguay. Soil laboratory analyses, including physicochemical properties, SOC content, bulk density and eDNA-derived biodiversity metrics, strengthen model training and validation. By unifying EO, laboratory and field-based measurements, the project overcomes the disconnect between point-based observations and landscape-scale prediction for carbon market stakeholders.

A key outcome is the creation of high-resolution SOC, biomass, and biodiversity geolayers that improve upon existing global datasets and are applicable across forest and agroforestry systems. These outputs will be deployed in a visualization platform, offering intuitive dashboards that support decision-makers, carbon project developers, conservation NGOs, and certification bodies. The system provides an accessible interface for understanding soil health, mapping co-benefits, and strengthening MRV processes in voluntary carbon and biodiversity markets.

The project contributes to the democratization of DSM by reducing technical barriers, improving data transparency and providing scientifically validated, easily interpretable soil information. Ultimately, SOCBIO-MAP strengthens global capacity to monitor soil health, supports evidence-based land management and advances high-integrity nature-based solutions aligned with climate, biodiversity and sustainability goals.

**Acknowledgments**

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# Digital Soil Mapping Plus Complexity Analysis: an Effective Approach to Identify Sensitive Areas of Landscape Evolution

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**ABSTRACT**

Digital Soil Mapping (DSM) can obtain a large amount of soil data, which can offer critical data support for revealing the mechanisms underlying soil landscape evolution. Soils exhibit various development trends due to differences in initial conditions and external driving forces, leading to the spatial and temporal variation in their properties. This study integrates DSM with a modified evolutionary pathway approach which is based on Δcomplexity. Horizontal and vertical soil heterogeneity across an agro-pastoral transitional zone (APTZ) in northern China was quantified. Particle size distribution (PSD) and magnetic susceptibility (MS) were focused on, and, on the basis of soil property resulting maps, Δcomplexity between different soil depths was quantified to provide valuable insights into soil-landscape evolution. This study measured the PSD and MS of 1317 samples and determined Δcomplexity for 148 catchments in the study area. The $R^2$ for the prediction accuracy of DSM ranged between 0.481 and 0.729. The Δcomplexity of PSD spans from -0.089 to 0.042 % $cm^{-1}$ for both deep and shallow layers, whereas that of MS ranges from -0.6 to 0.96 10-8 $m^3$ $kg^{-1}$ $cm^{-1}$. Vertical heterogeneity, which is determined by the positive or negative shifts (convergent or divergent) in Δcomplexity in every 5cm soil, is primarily associated with soil forming factors such as parent material, topography and vegetation, and it is further regulated by tree throw and human activities. For horizontal heterogeneity, which derived from pedogenesis and also soil redistribution induced by both water and wind erosion, is determined by the positive and negative variations in both shallow and deep complexity. Our approach enables the identification of highly heterogeneous areas that may be particularly sensitive to soil change and degradation. It offers a transferable framework for assessing soil development and guiding sustainable land use. Δcomplexity can be used to capture the dynamic changes in soil properties along the soil profile on the basis of the large amount of data obtained from DSM, the combination of DSM and the soil Δcomplexity metric provides a promising tool for analyzing and visualizing the state and trends of soil-landscape evolution.

# Projected intensification of soil salinization in global drylands under future aridity increase

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## ABSTRACT

Soil salinization is a major threat to agricultural production, water management, and ecosystem health. Although climate change is projected to expand global drylands, the response of future spatiotemporal changes in global drylands soil salinity, especially in croplands, to increased aridity remains unclear. Here, we develop machine learning prediction models using the last 20-year global soil salinity measurements combined with climatic, anthropogenic, geological, and remote sensing data to provide future changes in soil salinization. Our results reveal that saline soil areas in drylands are projected to expand with rising aridity. In dryland croplands, transitions to saline soils are projected to occur predominantly within irrigated areas. These findings offer crucial insights into the future changes in dryland saline soils around the globe, thus informing the development of more effective soil salinity monitoring and management strategies.

# Spatial distribution and formation environment of rock fragment layer in black soil region of northeastern China

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**ABSTRACT**

Soil gravel plays a crucial role in regulating water-air transport and ecological processes. Due to complex pedogenic processes, the spatial distribution of soil gravel often exhibits high heterogeneity, making accurate mapping of its spatial distribution a challenging task. This study collected 1,176 soil profile data points from the black soil region of Northeast China (427 profiles with gravel and 749 without gravel). By integrating topographic and multispectral remote sensing data, a random forest model was employed to predict the spatial distribution of soil gravel in the region. The predictive model was evaluated using 30% of the data as validation, achieving a ROC-AUC of 0.83 and an F1-score of 0.74. The prediction results indicate that the probability of soil gravel occurrence is high in the following areas: the river floodplains of the Songhua River basin in the Sanjiang Plain, the river valley zones of the Songliao Plain along the middle reaches of the Liao River, and the foothill slopes and gullies of the Greater and Lesser Khingan Mountains and the Changbai Mountain range. The study also conducted an in-depth uncertainty analysis and revealed factors influencing the spatial differentiation of gravel layers. The distribution of soil gravel is affected by topography and land use types, which aligns with the finding that MRVBF and soil thickness hold the highest importance in the predictive model. The machine learning model developed in this study can provide reliable data support and technical methods for accurate carbon stock estimation, cultivated land quality monitoring, and sustainable land resource management in the black soil region of Northeast China.

**Acknowledgments**

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# UAV assisted high-resolution mapping of soil organic carbon and nitrogen in the mattic layer of the Tibetan alpine meadow

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**ABSTRACT**

Alpine meadows in the Qinghai-Tibetan Plateau (QTP) play a crucial role in global carbon and nitrogen cycles. Due to the unique environmental conditions and complex soil processes in the region, accurately quantifying the spatial distribution of soil organic carbon (SOC) and total nitrogen (TN) concentrations in these ecosystems remains a major challenge. The study effectively utilized UAV-based digital elevation models (1-m resolution), spectral data, and machine learning techniques (i.e., geographical weighted regression, gradient boosting regression tree, random forest, combined with residual kriging) to predict SOC and TN in the mattic layer of the typical alpine meadow ecosystem of the QTP. A total of 62 soil samples from the mattic layer were collected from the study area, and the mattic layer depth was also recorded. The performance of the prediction models were evaluated on 30% test data considering R2, MAE, and RMSE. The random forest residual kriging model provided the highest prediction accuracy for SOC and TN, with $R^2$both being 0.69, MAE 12.39 and 0.36, respectively, and RMSE 14.83 and 0.46, respectively. The SOC content of the soil in the mattic layer of the meadow ecosystem is 51.36-106.90 g $kg^{-1}$, and the total nitrogen content is 3.41-5.81 g $kg^{-1}$. The study also conducted an in-depth analysis of uncertainty and revealed the factors affecting the distribution of SOC and TN. Areas with large topographic fluctuations had higher uncertainties in the distribution of SOC and TN. Topography was the most important factor controlling the distribution of SOC and TN. These results provide valuable insights into predicting the carbon sequestration potential of alpine meadows, which is crucial for global climate regulation, and the maps can be useful in grazing and soil management priorities. Future research will test prediction models by utilizing anthropogenic factors such as grazing intensity and additional sampling from high-uncertainty areas and assess their importance and interpretations.

# Development and Applications of a Soil Spectral Library in Hainan, China

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**ABSTRACT**

Soil organic matter (SOM) is a key indicator of soil quality, agricultural sustainability, and the carbon cycle. Visible–near infrared (Vis–NIR) spectroscopy enables rapid, non-destructive soil assessment, but model robustness remains limited in tropical regions where intense weathering, acidic conditions, Fe/Al oxide enrichment, and diverse land use create complex spectral backgrounds. This study presents a regional soil spectral library for Hainan Island, China, and its application for SOM prediction.

From May to July 2025, a large-scale spectral campaign was conducted in Haikou using samples from the Third National Soil Survey. Approximately 6,000 soil samples were organized, about 4,800 laboratory spectra of 2-mm sieved samples and 3,000 moisture experiment spectra were acquired, and around 6,000 physicochemical records are expected to be linked. A standardized workflow was established for sample preparation, white-References calibration, spectral scanning, preprocessing, and data storage. Digital tools supported sample–spectrum registration, batch renaming, spectral averaging, and standardized output. The library links sample identity, metadata, spectra, physicochemical properties, and quality-control information.

Two applications demonstrate its value. First, a texture-aware framework was tested using 270 agricultural topsoil samples classified as sandy, loamy, and clayey soils. Spectra were processed using SNV and SNVBA; CARS was used for feature selection; and PLSR and RF models were compared. Texture affected spectral behavior and model performance. SNVBA improved loamy and clayey spectra, while CARS mainly benefited PLSR. RF achieved high and stable performance across texture and preprocessing combinations, with most $R^2$ values above 0.85. These results support texture stratification, preprocessing adaptation, and RF-based nonlinear modeling.

Second, a mechanism-guided covariate compensation strategy was developed using 608 highly weathered tropical acidic topsoil samples. Bayesian network analysis identified DTPA-extractable Fe (AFe) as a key background variable associated with SOM spectral responses. Band-wise correlation revealed SOM–AFe spectral overlap, especially around 1550–1750 nm, indicating that overlap bands contain both SOM information and Fe-related interference. Removing overlap bands alone did not clearly improve prediction. In contrast, adding water content, electrical conductivity, and AFe improved PLSR performance. The final fusion model achieved $R^2 = 0.670$, RMSE = 2.92 g $kg^{-1}$, RPD = 1.77, and RPIQ = 2.19, increasing $R^2$ by about 59.9% and reducing RMSE by about 24.7%.

Overall, the Hainan Soil Spectral Library is a standardized, traceable, and scalable prototype for tropical soil spectral infrastructure. By combining library development, texture-aware modeling, and mechanism-guided covariate compensation, this study provides an interpretable pathway for robust SOM prediction in highly weathered tropical soils.

**Acknowledgments**

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# From Mars to Farmland: Next-Generation In-Situ Soil Composition Monitoring Technology for Agricultural Fields

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**ABSTRACT**

Rapid in situ field quantification of soil constituents remains a global challenge. Inspired by the SuperCam spectroscopic technology deployed on NASA's *Perseverance* Mars rover, we pioneered a novel methodological and theoretical framework for multimodal laser spectroscopic sensing of agricultural soils. Based on this framework, we led the development of an on-site field sensor capable of directly and accurately measuring multiple soil nutrients and contaminants under field conditions.

**Theoretical advances:** We established the field of multimodal laser soil spectroscopy by enabling synchronous measurements of scattering, absorption, and fluorescence through a shared optical path, together with deep fusion of multimodal signals. To address key bottlenecks such as the highly complex soil matrix and the ultratrace concentrations of heavy metals, we developed a new fluorescence-resonance LIBS sensing paradigm, which enhances signal intensity by 2–3 orders of magnitude and enables rapid detection of heavy metals down to 150 *ppt*, setting a new record for the lowest detection limit in spectroscopic sensing. We also proposed a new theory of laser-ablation-coupled absorption spectroscopy and, for the first time, achieved rapid in-field detection of soil microplastics.

**Technological application:** We developed the in situ soil sensor "SmartSoil", which can measure three major categories of soil properties—nutrients, heavy metals, and trace elements—covering 36 indicators within 10 minutes. These include total nitrogen, nitrate nitrogen, available phosphorus, multiple heavy metals, microplastics, and other key parameters. The system is supported by independent intellectual property rights and protected by 16 Chinese invention patents and 3 international patents. "SmartSoil" has been selected for the "Sci-Tech Innovation China" Pioneer Technology List, the Top 10 Original Smart Agriculture Solutions for Beijing Smart City Scenarios, the National Top 10 Recommended Technologies for Smart Agriculture Science and Innovation, and the Beijing Catalogue of First Major Technological Equipment.

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# Stacking ensembles with spatial residual correction for improved soil pH mapping in tropical croplands

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**ABSTRACT**

Soil acidification is a critical constraint on sustainable agriculture in tropical regions where accurate soil pH mapping is essential for informed soil management and ecological assessment. However, existing digital soil mapping (DSM) approaches often struggle to capture both the complex nonlinear relationships among environmental covariates and the spatial dependence inherent in soil pH, especially for at a regional scale. To address this gap, we developed a hybrid modeling framework that integrates ensemble machine learning with spatial residual correction. Using Chengmai County located in south China as a case study, soil pH observations were combined with multisource environmental predictors, including long-term remote sensing imagery, topographic variables, and historical soil information. A stacking ensemble model, built from Random Forest, XGBoost, and CatBoost, was first trained to capture nonlinear patterns. The residuals from this model were then refined using Geographically Weighted Regression (GWR) to account for local spatial variation. Results demonstrate that integration of ensemble learning with spatial regression substantially improve the accuracy of soil pH mapping (R2 of 0.67). This approach provides a robust tool for monitoring soil acidification and guiding sustainable agricultural management in tropical croplands.

**Acknowledgments**

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# Standardized Soil Water Deficit Index for Monitoring Agricultural Drought in India with a Machine Learning Extended Root Zone Soil Moisture Dataset

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## ABSTRACT

Soil moisture status is crucial for agricultural drought assessment. The satellite-derived Soil Moisture Active Passive Level-4 (SMAP L4) modelled root zone soil moisture (RZSM) product, with its 9 km spatial resolution, is suitable for this purpose. However, its availability from 31st March 2015 onwards limits its applicability for the computation of robust drought indices. To address this gap, we used an ensemble machine learning approach—Random Forest (RF) regression with dynamic and static inputs—which outperformed other models on the independent 2021 validation set, achieving the highest coefficient of determination ($R^2$ = 0.74–0.81) and the lowest root mean square error (RMSE = 0.026–0.044), compared with Artificial Neural Networks ($R^2$ = 0.19–0.32, RMSE = 0.083–0.175), Support Vector Machines ($R^2$ = 0.03–0.27, RMSE = 0.063–0.125), and Classification and Regression Trees ($R^2$ = 0.65–0.73, RMSE = 0.032–0.052). This trained RF model predicted SMAP L4 RZSM for 2001-2015, combining with actual data from 2016-2021 to form a 21-year continuous long-term dataset used to compute the Soil Water Deficit Index (SWDI, Martínez-Fernández et al., 2015) and its standardized form, Standardized Soil Water Deficit Index (SSWDI). The SSWDI mitigated the SWDI's tendency to overestimate drought areas and proved more effective for capturing droughts during the monsoon *(kharif)* crop season across India. The SSWDI accurately identified maximum drought-affected areas in known severe years such as 2002, 2009, 2012, 2014, and 2015, as reported by government agencies, and showed a stronger correlation with the 3-month Standardized Precipitation Index (0.45) compared to the trend-adjusted Vegetation Condition Index (0.28). Additionally, SSWDI showed a strong correlation with the Standardized Normalized Agricultural Gross Primary Productivity (SNGPP; $p < 0.1$, $R > 0.6$)—computed by removing the technological time trend from Agricultural Gross Primary Productivity (Gangopadhyay et al., 2022)—particularly in rainfed regions and the late crop season. By leveraging site and spatial data with machine learning to extend SMAP RZSM, this work provides a nationally consistent soil moisture baseline and a robust, standardized drought index SSWDI, tailored for agricultural drought monitoring. Future work could integrate multiple indicators such as rainfall, soil moisture, evapotranspiration, and vegetation into a comprehensive drought index for even more holistic drought monitoring.

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# Soil Fertility Index and Spatial Variability as Drivers of Site-Specific Fertilizer Management in the Tigray Highlands

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**ABSTRACT**

Agriculture is central to Ethiopia's economy, yet increasing population pressure and unsustainable farming practices have led to severe soil fertility depletion and land degradation, particularly in the Tigray region highlands. This study assessed soil properties conditions in the Seret and Adigolo sites of Tigray region, aiming to develop the Soil Fertility Index (SFI), identify its key determinants, and support the development of site-specific fertilizer recommendations. The research was conducted using field surveys, grid-based soil sampling, laboratory analysis, Principal Component Analysis (PCA), and GIS-based spatial interpolation for soil property mapping. It was identified that there was significant variability in soil properties across the sites. Both Seret and Adigolo soils were characterized by nearly neutral pH, low EC, and high cation exchange capacity (CEC), indicating favourable conditions for crop production. However, both sites showed critical nutrient limitations particularly low levels of available P, Zn, TN, and low to moderate SOM primarily due to continuous cultivation, poor organic input, and erosion. PCA revealed six minimum soil fertility indicators (MSFIs) most relevant to assessing soil health, and these were used to calculate the SFI. Spatial analysis showed that almost 100% of farmland in Adigolo had Moderate SFI and, compared to 94.3% moderate and 5.7% low in Seret site. These differences reflect varying land management and soil fertility status. These results emphasize the need for site-specific fertility management using organic amendments, macronutrients and micronutrients mineral fertilizers, and conservation practices to sustain productivity. The SFI can be used as a diagnostic tool for guiding tailored interventions that improve input use efficiency, maintain yield performance and enhance smallholder livelihoods.

**Key Words:**Principal Component Analysis, soil fertility index, ordinary kirging, Minimum Data Set, interpolation

# Well-facilitated Farmland Construction enhances soil organic carbon storage in China

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**ABSTRACT**

Soil organic carbon (SOC) is central to regulating the global carbon cycle and underpinning food security, yet unsustainable cultivation has resulted in a continuing SOC loss and has made it highly vulnerable to climate change. In China, the Well-Facilitated Farmland Construction (WFC) initiative has sought to enhance soil conditions by integrating farmland management units (FMUs) and adopting improved practices, including optimized irrigation, straw incorporation, and targeted fertilization strategies. Since its launch in 2013, the WFC project has been implemented across more than 50 million hectares of farmland in China. However, its spatio-temporal impacts on SOC remain poorly understood. To address this gap, we focused on three representative regions, Shunyi, Rudong, and Dangtu, to examine the impact of FMU integration. A total of 1,549 soil profiles were compiled to calibrate the process-based CENTURY model and simulate long-term variations in topsoil (0-20 cm) SOC density (SOCD) across Chinese farmlands. Results show that, following the WFC project, farmland fragmentation decreased while SOCD increased, with strong negative correlations between fragmentation degree and SOCD (-0.88 in Shunyi, -0.94 in Rudong, and -0.52 in Dangtu). These findings indicate that farmland patch integration contributes significantly to SOC sequestration. By comparing future SOC trajectories under traditional versus WFC practices, we found that WFC management offers substantial sequestration potential, increasing SOC stocks by 3.34 Pg under SSP1-2.6 and 2.86 Pg under SSP5-8.5 during 2030-2100 in Chinese farmlands. This sustained increase reflects the synergistic effects of fertilization and elevated $CO_2$, enhanced crop productivity through optimized irrigation, greater organic inputs from straw incorporation, and reduced microbial decomposition under balanced nitrogen fertilization. In conclusion, WFC demonstrates a scalable pathway toward more resilient and climate-smart food systems.

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# Spatiotemporal divergence of soil acidification in China's cropland

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**ABSTRACT**

Soil acidification in China's croplands, driven by intensive agriculture, threatens both agricultural sustainability and ecological security. However, its large-scale spatiotemporal dynamics and underlying drivers remain poorly understood. We developed a meta model coupling of process model and machine-learning, integrating national soil survey information from the Chinese Soil Series Records and the VSD+ model to simulate and map soil pH trajectories from 1980 to 2100. We found a pronounced national acidification trend from 1980 to 2020, with average cropland soil pH declining by 0.37 units (from 7.05 to 6.68). This trend varied regionally, with the most severe acidification in Northeast China (ΔpH = -0.67) and the slowest decline on the Qinghai-Tibet Plateau (ΔpH = -0.11). Projections show that even under a nitrogen fertilizer zero-growth scenario, soil pH will continue to decrease to 6.49 by 2100. Our model reveals that fertilizer management exerts a stronger influence on acidification than climate change, as evidenced by minor differences among climate scenarios. Mechanistically, nitrogen transformation was the dominant acidifying process in upland systems, while both $HCO_3$ leaching and nitrogen transformation were primary drivers in paddy systems. This study provides a quantitative basis for sustainable nutrient management and offers valuable insights for mitigating soil acidification in global agricultural systems.

**Acknowledgments**

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# Global hotspots of soil microplastics and their drivers

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**ABSTRACT**

Microplastic pollution in agricultural soils threatens global food security by degrading soil health and reducing crop productivity. Despite continuous inputs from sources like plastic mulch and fertilizers, the global distribution and key drivers of this contamination are poorly understood. In this study, we synthesize a comprehensive global database of soil microplastic measurements. We integrate this database with key anthropogenic and environmental predictors in a knowledge-guided machine learning model to generate the first high-resolution global map of soil microplastic contamination, and identify its dominant drivers. This map identifies critical high-risk regions, providing a scientific foundation for targeted ecological risk assessment and sustainable soil management.

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# Assessing human activity impacts on soil nutrient condition in Australia.

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**ABSTRACT**

Human activities, particularly intensive agriculture over the past 200 years in Australia, have significantly impacted soil properties due to European settlement. These impacts are especially evident in key soil nutrients such as soil organic carbon (SOC), nitrogen (N), phosphorus (P), and potassium (K). However, there is still a lack of robust approaches to quantify how soil nutrients have changed under human influence over the continent.

In this study, soil samples were collected across Australia in regions receiving between 500 and 600 mm of rainfall, as these areas are more likely to experience agricultural activity. Sampling points were spaced approximately 100 km apart. At each location, representative soils, identified using pedogenon mapping, were collected from both native vegetation and intensively managed agricultural land within a 30 km buffer.

A total of 273 soil samples were collected and analysed. We compare soil pH and nutrient levels (SOC, N, P, and K) across different land uses and major pedoclimatic regions (eastern, western, and central Australia). We show SOC levels in agricultural areas were lowered than in natural vegetation areas due to soil disturbance and reduced organic inputs. However, fertiliser application in agricultural lands results in elevated concentrations of other nutrients and soil pH. By quantifying these differences, we aim to evaluate how much soils have changed due to human activities and provide farmers with practical recommendations for improving land management and supporting long-term soil security.

# WoSIS: An international effort to share standardised soil data for the world

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**ABSTRACT**

WoSIS is a Soil Information System composed of a large soil database; application programming interfaces (API); workflows; dashboards and more. It is developed and maintained by ISRIC with the aim to: safeguard world soil profile data; quality-assess and harmonise/standardise the data; and subsequently serve the shared data to support digital soil mapping and a range of environmental applications.

WoSIS provides a growing number and range of quality-assessed and standardised soil profile data for the world. The system draws on voluntary contributions from numerous data holders/providers worldwide who are willing, and able, to share their data for the greater benefit of the international community. In return, the data providers will get the following for their datasets: a dashboard with various summaries of the contents of the datasets, links to download the datasets in a variety of formats and standards, and if required a DOI to facilitate findability and citeability. A thorough (mostly automated) standardization and harmonization process improves the consistency/comparability of the ingested data; source data quality, however, remains the responsibility of the data provider.

WoSIS data ingestion follows a strict protocol integrating reproducible programmatic data cleaning, ETL (extract, transform and load) rules to harmonize and standardise data using a GraphQL API. The

ETL workflow validates, harmonises, and structures contributed datasets in accordance with WoSIS data model based on the ISO 28258 standard. Submitted soil profile data undergo automated structural checks such as detection of overlapping horizons, implausible values, unit inconsistencies, and vocabulary mismatches. WoSIS never alters the original data. Instead, during data entry, the system flags potential issues for the contributor, who remains responsible for resolving them by either correcting the data or removing the affected records before re-submission; only ‘error free’ datasets can enter WoSIS.

The ETL pipeline is powered by a schema-guided GraphQL API that allows users to upload and check/refine their own datasets, while the ISRIC WoSIS team can perform the ingestion on behalf of providers using the same procedures, in particular for large datasets.

In this presentation we are going to discuss the principles of WoSIS data ingestion and illustrate the latest developments for the API for checking, querying and uploading soil datasets into WoSIS itself, for further distribution to the international community.

# Low-Cost Sensors for Monitoring Soil Condition in Landscape Restoration

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**ABSTRACT**

Soil is not consistently monitored despite its critical role in ecological function. One of the primary barriers to widespread soil monitoring is cost, which limits the ability to collect long-term, spatially distributed data. To address this gap, we deployed low-cost wireless soil moisture (AUD 60) and temperature (AUD 5) sensors at a site undergoing rehabilitation. The project aims to improve soil moisture retention through management interventions such as netting and wooden stakes to facilitate landscape revegetation.

Twenty-seven sensor stations were installed across an area of 2.81 km2, with each station including two soil moisture sensors installed at depths of 5 cm and 30 cm and soil temperature, pH and electrical conductivity (EC) sensors installed at a depth of 5cm. The soil moisture sensors have responded consistently to rainfall, drying events, and diurnal temperature and transpiration cycles over the first five months of operation. These responses aligned with event magnitude (i.e. larger rainfall events produced larger moisture changes), indicating efficacy in data monitoring from these low-cost sensors on these time scales.

The region was also progressing into drought during this time, which provides crucial data of landscape responses during hydrological extremes. On average, control sites (with higher vegetation cover) reported higher surface soil moisture (5 cm) than rehabilitated sites, likely due to natural differences in site conditions. At 30 cm depth, moisture readings were more comparable across sites. Surprisingly, scalded sites exhibited elevated soil moisture at both depths. This may be attributed to their proximity to a gully, where runoff accumulates. However, a more plausible explanation is that soil disturbance during sensor installation resulted in looser soil, temporarily increasing infiltration rates. These findings highlight the promise of low-cost sensors as scalable tools for enhancing soil monitoring in restoration contexts, particularly during periods that are subject to environmental stress such as drought and their impacts on the sub-surface

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# Using legacy data and geostatistics for assessing soil organic change in the Sele River Plain (southern Italy)

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**ABSTRACT**

The recent approval by the European Parliament of the Soil Monitoring Law is a major step forward monitoring and assessing EU soils in the perspective of the path to healthy soils. Legacy datasets of soil properties, such as soil organic carbon (SOC), represent valuable resources for establishing SOC baseline and for assessing changes in SOC when multiple datasets from different time periods are available. In this study two SOC datasets (2003 and 2016/17) were analyzed to establish a baseline and to assess SOC changes in the Sele Plain (southern Italy). This area is characterized by intensive horticulture, with ready-to-eat leafy vegetables, representing a major economic driver. Decline in soil fertility resulting from such intensive practices remains a critical concern. The datasets were generated using different sampling designs with no resampling involved. Following preliminary checks, soil samples within the study area were selected from the two datasets (129 for 2003 and 168 for 2016/17). A statistical and spatial analysis was carried out as first analysis and different geostatistical methods were applied to analyze and understand spatial and temporal variation of SOC. After a univariate structural analysis, omnidirectional spherical models of variograms were fitted for both SOC2003 and SOC2016/17. Then, 200 realizations were simulated using turning bands simulation (TBS) to better visualize heterogeneity and assess uncertainty for both datasets. From the simulated SOC values for each pixel of the simulation grid, maps of 'expected' values at any location and the related standard deviations were obtained. The standard deviation provided a measure of uncertainty on the 'true value' of SOC. The SOC difference map between SOC2003 and SOC2016/17 enabled to visualize the spatial pattern of changes. To account for the different soil sampling designs, polygon kriging was used to estimate SOC values across soil unit polygons. Polygon kriging provides estimates of the expected value for each polygon along with a standard deviation. Within a Gaussian framework, the latter was used to calculate confidence intervals and to test whether the expected values for each soil unit in 2003 and 2016/17 were statistically different. To interpret temporal changes in SOC, a geostatistical tool known as pseudo cross variogram was applied. This method is used when two variables (in this case, SOC in 2003 and 2016/17) are measured at different locations, and it estimates spatial correlation by pairing nearby points from the two datasets. The pseudo cross variogram results revealed heterogeneous spatial variability: some areas exhibited marked changes, whereas others remained relatively stable. Direct variograms revealed higher SOC spatial variability in 2016/17 than in 2003, likely due to management or vegetation changes. The variogram of the SOC difference (2016/17 minus 2003) increased with distance, suggesting a coherent spatial pattern rather than random noise.

# Quantifying Pan-European Soil Organic Carbon Trends and Associated Uncertainty for Soil Health Monitoring

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**ABSTRACT**

Soil organic carbon (SOC) is one of the key soil health indicators and thus a central property for large-scale soil monitoring and reporting. However, quantifying SOC change across large spatial and temporal scales remains challenging due to heterogeneous data sources, scale effects, and uncertainty inherent in predictions derived from machine learning models. Robust and transparent analytical frameworks for estimating SOC change are therefore required to support reliable soil health monitoring and informed decision-making.

In this study, we present pan-European spatial estimates of SOC trends in agricultural and forest land uses. We used harmonized spatio-temporal SOC predictions for the period 2000–2021, derived from machine-learning models that integrate soil observations from various European soil inventories together with satellite-derived products and other environmental covariates. Pixel-wise SOC trends were estimated at 30 m spatial resolution using linear regression models, and trend uncertainty was quantified using upper and lower bounds of prediction intervals. To enhance interpretability for soil monitoring applications, we further developed a spatial agreement metric that identifies areas where the direction of SOC change is consistent across uncertainty bounds, thereby delineating regions with robust trend signals.

Our results reveal pronounced regional contrasts in SOC trends across Europe. SOC declines are observed in many regions of eastern Europe and in parts of western and northwestern Europe, including the United Kingdom, whereas large areas of central Europe exhibit relatively stable SOC levels. In contrast, parts of northern Europe, such as Sweden, show increasing SOC trends. These spatial patterns likely reflect interactions between climate conditions, land-use history, and long-term management practices.

Maps of uncertainty and agreement demonstrate substantial spatial variability in the reliability of SOC trend estimates. Northern regions, such as Norway, generally exhibit higher uncertainty, while countries such as France and Germany show comparatively low uncertainty, highlighting spatial differences in the confidence of SOC trend estimates for soil health monitoring.

This work demonstrates how integrating soil data, spatial modelling, machine learning, and uncertainty analysis supports large-scale, transparent monitoring of soil health indicators beyond static soil property maps, contributing to scalable soil monitoring and soil carbon reporting initiatives.

**Acknowledgments**

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# Modeling of spatiotemporal heterogeneity of agrochemical properties of soils within the territory of testing agricultural crop varieties

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**ABSTRACT**

The paper considers the problem of assessing and modeling the spatial and temporal heterogeneity of key agrochemical properties of the soil (hydrolyzable forms of nitrogen, mobile forms of phosphorus and potassium) in the territory of the variety testing site (80 ha) of the Republic of Tatarstan (Russia). The heterogeneity of soil indicators is a significant source of errors in assessing the productivity and adaptive potential of new varieties and hybrids, which can lead to biased conclusions and slow down breeding progress. Based on data from a detailed agrochemical survey and long-term monitoring of the site's soils (1987-2025), the spatial and temporal heterogeneity of agrochemical properties of soils was modeled using a digital soil mapping approach based on machine learning methods (random forest). The spectral indices of the Landsat 5/8 satellites of open and vegetation-covered soil, as well as the morphometric attributes of the SRTM digital relief model, were used as predictors of the heterogeneity of soil indicators. Spectral indexes for different years were calculated based on the Google Earth Engine service. The NDVI, SAVI, BSI, and NBR2 spectral indexes, as well as individual bands of Landsat 5/8 satellites, were used as dynamic indexes. The estimation of modeling uncertainty was carried out using the quantile regression forest (QRF) approach using the PICP prediction interval coverage probability indicator (PICP). It is shown that from 1987 to 2025, the site is heterogeneous in the content of nutrients. The coefficient of variation of soil properties varies significantly: for hydrolyzable nitrogen from 25% to 13%, for mobile forms of phosphorus and potassium from 25% to 32%. Based on the modeling results, it was revealed that using random forest models, depending on the year of observation, it was possible to describe 53-78% of the spatial heterogeneity of the content of hydrolyzable nitrogen, 66-76% of the heterogeneity of mobile phosphorus and 55-72% of mobile potassium. According to the analysis of Shapley numbers, the relative contribution of predictors to the spatial distribution of agrochemical properties is unstable: in some years, the spatial distribution of indicators is better described by remote sensing data, in others by terrain characteristics. Based on the results of the work, recommendations are proposed for optimizing the planning of field experiments, stratification of plots and adjustment of yield results taking into account the identified soil trends.

**Acknowledgments**

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# Measuring Ephemeral Gully Morphology Using a Portable Gulliometer and Image- based Techniques

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## ABSTRACT

Soil erosion, a critical environmental challenge, is exacerbated by factors such as intense rainfall, strong winds, and flowing water, leading to the formation of gullies. Among these, ephemeral gullies (EGs), characterized by their transient nature and formation due to concentrated overland flow, present unique challenges in soil conservation. Despite their significant impact on soil degradation, EGs have been relatively understudied, primarily due to their temporary existence and the limitations of existing measurement techniques. Addressing this gap, our study introduces a novel, cost-effective approach for the quantification and analysis of EGs. We have developed a Pin-artboard tool (Gulliometer), specifically designed for capturing the morphology of EGs in a field setting. Complementing this tool, we employed an advanced image-processing technique to accurately quantify the cross-sectional area of EGs with minimal error. This technique enables the calculation of EG volume by integrating cross-sectional profiles obtained at closely spaced intervals. Our methodology offers a significant improvement over traditional modeling approaches and field-based methods, which are often constrained by extensive data requirements, high costs, and limited applicability in varying field conditions. The Gulliometer, combined with our image-processing technique, provides a reliable, efficient, and accessible means of studying EGs, thereby contributing valuable insights into soil erosion dynamics. This approach not only enhances our understanding of ephemeral gully erosion but also aids in the development of effective soil conservation strategies and informed decision-making in land management.

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# A streamlined soil database strengthening near-real-time interoperability for soil monitoring networks and services

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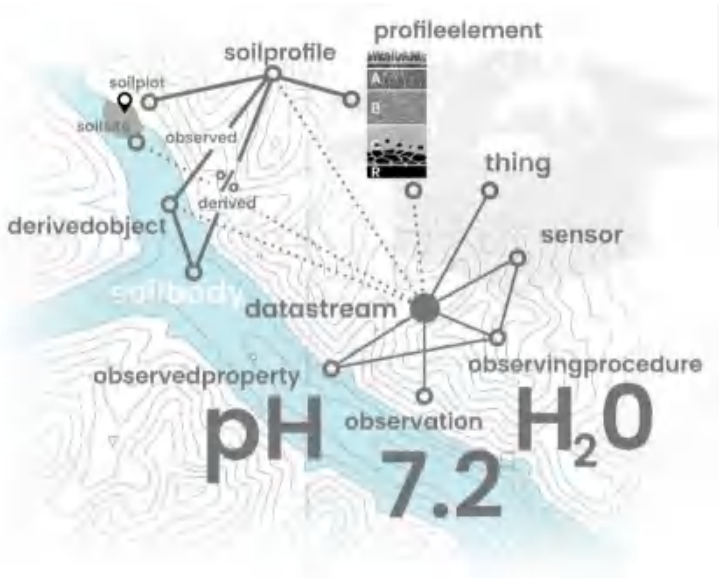
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## ABSTRACT

The European Commission recently adopted the 'Soil Monitoring Law', aimed to establish a soil monitoring framework to maintain EU soils in a healthy condition and to prevent and address all aspects of soil degradation, with a view to achieving healthy soils by 2050 (November 2025). Soil geospatial data also fall under the remit of the INSPIRE Directive (2007), aimed to establish an infrastructure for spatial information in Europe to support Community environmental policies. While the default encoding of INSPIRE Soil data is XML based GML, INSPIRE officially endorsed GeoPackage encoding rules as a Good Practice (November 2022), enabling the GeoPackage format to be used as an additional or alternative to the GML format. The European Joint Programme Soil (EJP SOIL) horizon 2020 research project, with the aim to streamline the transcoding and harmonization of national agricultural soil datasets towards INSPIRE-compliant sharing, developed a "Software framework for a shared agricultural soil information system", published on GitHub. The framework builds on three pillars: a streamlined soil database encoded in GeoPackage format, robust data transformation pipelines, and semantic harmonisation with managed code lists. In line with INSPIRE Good Practices, a logical GeoPackage model for the INSPIRE Soil theme was derived from the INSPIRE conceptual model, implemented and validated for INSPIRE-compliance. The INSPIRE-SOIL Geopackage was accompanied by executable transformation rules and templates, to ensure technical compliance and usability inside GIS environments. Building on these foundations, the Horizon Europe project SoilWise, aimed at providing an integrated and actionable access point to scattered and heterogeneous soil data and knowledge in Europe, is producing a revised version of the INSPIRE-SOIL Geopackage. A key novelty is the extension of the INSPIRE-SOIL Geopackage to align with the OGC SensorThings API 2.0 (STA2), enabling simple transfer between these formats. Specifically, STA2 defines ageospatial-enabled, RESTful data model and HTTP/MQTT bindings for creating, querying, and streaming observations consistent with the OGC/ISO Observations, and Measurements concepts, thereby strengthening near-real-time interoperability for soil monitoring networks and services.

Overall, the combined approach — INSPIRE-aligned GeoPackage encoding for structured soil datasets and STA2-based services for observational time-series — delivers a practical and future-proof pathway to interoperable soil information, therefore, contributing to FAIR principles. It is aimed at reducing provider burden, improving consumer usability, and bridging static and dynamic data flows in support of EU soil policies and the recently adopted Soil Monitoring Law.



# Step towards a 1:100,000-scale Soil Map of Italy supporting the implementation of a national soil monitoring network and service

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**ABSTRACT**

CREA, with the support of "Ministero dell'agricoltura, della sovranità alimentare e delle foreste" (MASAF), has been collaborating for years on the production of soil maps for Italy. The first printed version is dated 2012 (scale 1:1,000,000), and updated the previous one from 1966, in terms of both knowledge and methodologies.

On charge of "Ministero dell'Ambiente e della Sicurezza Energetica (MASE)", is to set in place an Integrated Monitoring System (SIM). MASE-SIM is a long-term surveillance/monitoring system to implement preventive measures for scheduled maintenance of the territory, optimizing the use of resources, and managing emergencies. This realizes, by others, goals of EU-wide framework for assessing and monitoring soils established by the Soil monitoring law (UE 2360/2025). The production of the Italian soils map at 1:100,000 scale is one of this framework application goals, the Precision Agriculture.

Map development requires the integration of information: cartographic and digital maps, collected soil observations through national, regional campaigns,or research institutions.

A new soil profiles survey campaign (n=1500) started on spring 2025 with the dual objective of intensifying spatial information (n=1350) and updating part of the previous data (n=150 out of about 27000), introduced by a training school for surveyors. The References manual for nationally harmonized soil survey (Costantini, 2008). was updated and a dedicated Soil survey App & Management portal was developed, with CREA support. This last was aligned to the "Software framework for a shared agricultural soil information system", produced within H2020 EJPSOIL Joint European Research Program, conforming soil data to the INSPIRE Directive (2007/2/EC).

These coordinated efforts aim to establish a harmonized national soil information system, of which the Italian soils map represents a key deliverable and will represent the spatial distribution of the main observed soils in the national territory.

**Acknowledgments**

Authors Acknowledge Ministero dell'agricoltura, della sovranità alimentare e delle foreste (MASAF) for founding of the work, Ministero dell'Ambiente e della Sicurezza Energetica (MASE) for the leading activity on setting the Integrated Monitoring System (MASE-SIM).

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# Reshaping Cropland Quality Monitoring through the Rational Use of Crowdsourced Data

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**ABSTRACT**

Cropland quality underpins food security and sustainable agriculture. However, existing monitoring networks lack systematic design, resulting in sampling redundancy, insufficient spatial coverage, and an urgent need for optimization. The proposed research focuses on the optimization strategies for cropland quality monitoring networks. Drawing on the framework of LUCAS-Copernicus, this research integrates existing monitoring networks with crowdsourced survey data. Multi-source remote sensing features further characterize sampling point attributes within a multidimensional feature space. Spatial statistical methods—including joint probability density distribution analysis, bin-based selection, and composite indicator evaluation—are applied to quantitatively assess the representativeness of candidate sampling points and to perform stratified selection. Ultimately, we refine the optimized network by considering monitoring priority levels and spatial distance constraints, incorporating field validation results to enhance robustness.

Participation in this conference will facilitate knowledge exchange among researchers, practitioners, and policymakers, fostering interdisciplinary collaboration in cropland quality monitoring. In addition, the integration of thematic baseline datasets, such as soil salinity maps, together with specialized monitoring networks constructed through sample size estimation and stratified sampling, demonstrates the scalability and adaptability of the proposed approach for addressing specific cropland quality issues. The anticipated outcomes are expected to support governmental agencies in optimizing cropland quality monitoring networks, thereby enhancing monitoring capacity, improving cropland management, and advancing understanding of cropland quality dynamics. This ABSTRACT is submitted with the objective of stimulating academic discussion and promoting sustainable land management.Thank you for considering this contribution.

# Spatio-temporal patterns and environmental controls of soil organic carbon stocks in global tidal wetlands since 2009

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## ABSTRACT

Tidal wetlands are important blue carbon sinks and a global research priority for climate mitigation due to their high carbon storage. While current global estimates of tidal wetland soil organic carbon (SOC) stocks mainly focus on individual wetland types and calculate changes based on wetland area changes, comprehensive assessments of SOC stocks across tidal wetland types and their dynamics remain scarce. By jointly accounting for spatio-temporal changes in both SOC density and wetland extent, this study provides the first spatially explicit and temporally resolved global assessment of SOC stocks and decadal changes across major tidal wetland types: mangroves, salt marshes, and tidal flats. Using a spatio-temporal digital soil mapping (ST-DSM) framework, we integrated global soil observations (5,489 locations, 42,154 soil layer records) with 62 environmental covariates to generate 90 m SOC maps at three depth intervals (0 ~ 30 cm, 30 ~ 60 cm, and 60 ~ 100 cm) for two time periods (2009-2014 and 2015-2020). Results reveal a global SOC decline from 8.80 (±0.09) Pg to 8.26 (±0.09) Pg (-6.1%), with greater losses in deeper layers. Low-latitude regions such as southern Asia and Africa were key loss hotspots. Mangroves showed the largest losses, mainly driven by decrease in SOC density. Tidal flats lost both SOC density and area, whereas salt marshes exhibited moderate gains caused by area expansion and SOC density increase. SOC losses were more pronounced in countries at lower-middle and upper-middle income levels. Driver analysis indicated that oceanographic and climatic factors were the dominant controls on SOC dynamics, although the key drivers for the three wetland types differed. Quantifying spatial and temporal variability of SOC at a global scale, this work reveals the magnitude and drivers of blue carbon change and underscores the need for targeted wetland conservation to support sustainable management and climate mitigation.

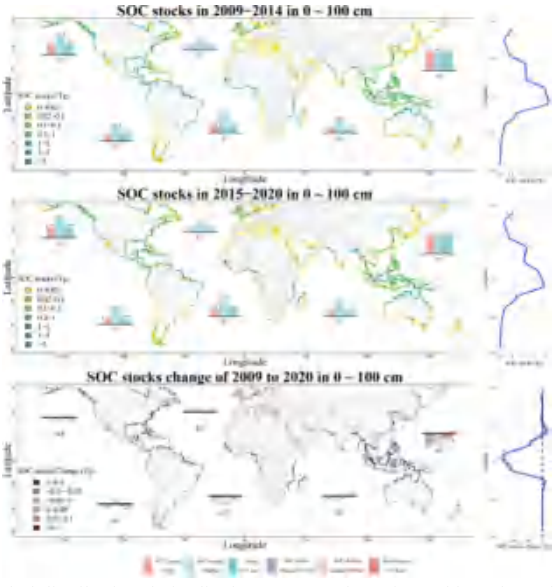



Fig 1 Aggregated per 0.5° cell results of global distribution, latitudinal patterns, and continental bar plots of soil organic carbon (SOC) stocks and their changes from 2009 to 2020 (0 ~ 100 cm soil depth). The bar graph shows the SOC stocks (Pg), SOC density (Mg/ha), and wetland area (103 km2) of each continent and their change.

**Acknowledgments**
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# Estimation of Salinization in the Yellow River Delta Based on BO-XGBoost and a Four-Dimensional Feature Space, with Spatiotemporal and Trade-off/Synergy Factor Analysis

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## ABSTRACT

Compared to traditional two- or three-dimensional feature spaces, a four-dimensional feature space can comprehensively account for the complex, coupled effects of multiple environmental variables on the formation and evolution of salinization—a approach that, to our knowledge, has not been previously reported. This study, focusing on the Yellow River Delta, constructed a total of 34 indices derived from Landsat 4/5/7/8/9 data, categorized into four types: salinity, water, vegetation, and others. The Bayesian-optimized XGBoost (Extreme Gradient Boosting) model was employed to screen for the optimal representative indices. Subsequently, an optimal salinization estimation model was developed based on the selected four-dimensional feature space. Using the gravity center model, the optimal parameter-based geographical detector model, and trade-off/synergy analysis, we analyzed and explored the spatiotemporal evolution patterns of salinization and its dominant influencing factors in the Yellow River Delta from 1985 to 2024. The main results indicate that:(1) The Bayesian-optimized XGBoost model effectively screened the indices, identifying SI1, SI, DVI, EVI, NEW, WI2019, COSR, and WET as the most suitable indices for characterizing salinization. (2) The four-dimensional feature space model (SI1-DVI-WI2019-COSR) achieved a high accuracy ($R^2$ = 0.916), demonstrating strong applicability for estimating salinization in the Yellow River Delta. (3) Spatial heterogeneity was observed across different salinization grades. Slightly salinized land accounted for the largest area (48.1%), while moderately salinized land accounted for the smallest (approximately 12.3%). Coastal areas exhibited more severe salinization. From 1985 to 2024, the annual mean salinization index showed a fluctuating downward trend over time. (4) The overall trend of salinization grade change was one of improvement. The most significant improvement occurred between 2005 and 2015, with an improved area of 36.33%. (5) The trade-offs and synergies among factors varied across different periods. The areal proportion exhibiting synergistic relationships between GDP, precipitation, DEM, and soil salinity generally showed an increasing trend, whereas the areal proportion showing trade-off relationships between these factors (GDP, precipitation, DEM) and soil salinity exhibited a decreasing trend.

# Interpretable salinization estimation model for Dongying City based on integrated multi-dimensional spectral indices with XGBoost-driven transformations

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**ABSTRACT**

Against the backdrop of intensifying global climate change and anthropogenic activities, soil salinization is becoming increasingly severe, posing a significant threat to agricultural production and sustainable development. This study collected sample data from Dongying City, Shandong Province as the research area, focusing on investigating the effectiveness of combining mixed-scale transformations and high dimensional spectral indices in model inversion. The research process involved spectral transformations, upon which hybrid transformations were constructed. Subsequently, sensitive spectral bands were identified, leading to the development of two-dimensional and three-dimensional spectral indices. These indices served as feature variables to construct three types of models: Extreme Gradient Boosting (XGBoost), Partial Least Squares Regression (PLSR), and Convolutional Neural Network (CNN). The optimal model was evaluated using SHAP interpretability analysis. The results demonstrate that the proposed processing methods effectively enhance band sensitivity, improve model accuracy and generalization capability. Index operations conducted across different spectral bands can enhance spectral sensitivity characteristics or suppress the influence of noise to some extent. The outcomes provide a theoretical framework for optimizing spectral indices. The analysis reveals the salt-response mechanisms and noise resistance differences among various indices, facilitating the advancement of salinization monitoring towards greater precision, intelligence, and cost-effectiveness.

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# Soil Salinity Inversion in the Yellow River Delta Based on BO XGBoost and 3D Spectral Feature Space

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**ABSTRACT**

Against the backdrop of intensifying global climate change, soil salinization has become increasingly prominent, posing serious constraints to the sustainable development of agroecosystems. Compared with two-dimensional feature space, three-dimensional (3D) feature space can integrate the influences of three environmental variables, yet related studies remain scarce. This research selected the Yellow River Delta as the study area. Based on Sentinel-2 imagery and utilizing its unique red-edge bands sensitive to vegetation, we constructed 24 spectral indices across three categories: vegetation indices, salinity indices, and other indices. Feature selection was performed using a Bayesian-optimized XGBoost model. On this basis, multiple 3D feature spaces were constructed, and the optimal 3D feature space was selected by evaluating regression coefficients between in-situ measurements and the feature space combinations. Subsequently, soil salinization in the Yellow River Delta was inverted. The results indicate that: (1) among vegetation and salinity indices, NDRE and SI5 were identified as the most important features; (2) among the 3D feature spaces, the NDRE–Albedo–SI7 combination achieved the highest accuracy ($R^2$ = 0.921), demonstrating good regional adaptability, while the ERVI–SI7–Albedo combination performed the worst ($R^2$ = 0.453); (3) spatial inversion results show that lightly saline areas were most widespread (32% of total area), mainly distributed in the estuary region, whereas severely saline areas covered the smallest proportion (10%). This study provides theoretical support for monitoring and controlling soil salinization in the Yellow River Delta.

# Mapping and validating the root zone plant-available water holding capacity in central Ethiopia

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**ABSTRACT**

Reliable maps of the root zone plant-available water holding capacity (RZ-PAWHC) are essential for assessing crop water availability and supporting climate-resilient agricultural planning. RZ-PAWHC is calculated by summing plant-available water holding capacity (PAWHC), adjusted for the soil fine earth fraction (SFEF), over the effective root zone depth (RZD). Existing Sub-Saharan Africa (SSA) maps of RZ-PAWHC rely on continental datasets and lack validation. We generated 100 m-resolution RZ-PAWHC maps for maize and wheat across central Ethiopia by integrating national soil datasets, digital soil mapping, pedotransfer function (PTF), and RZD derivation rules. Thirteen primary soil properties were mapped using Random Forest models, and two additional soil maps were obtained from Africa-SoilGrids. These were inputs to PTF to estimate volumetric moisture contents at field capacity and permanent wilting point, and to the RZD rules to determine RZD. A coarse fragment map was used to derive SFEF. RZD was defined as the shallowest of a restrictive soil layer, depth to bedrock, oxygen shortage, or a crop-specific maximum rooting depth. Prediction accuracy of the primary soil property maps ranged from a model efficiency of 0.17 for coarse fragments to 0.79 for pH-H2O. Derived maps showed substantial spatial variability in total PAWHC over 0–150 cm depth (122 ± 55 mm), with SFEF averaging 89%, and RZD (124 ± 28 cm) primarily constrained by bedrock (covering 45% of the mapped area) and oxygen shortage (22%). RZ-PAWHC maps had mean values of 91 mm for maize and 83 mm for wheat, with the lowest values in poorly drained, clay-rich soils. Compared with SSA maps for maize, the generated maps indicated higher RZ-PAWHC due to higher PAWHC, higher SFEF, and deeper rooting, with fewer restrictive layers. Validation against independent observations showed that the generated maps outperformed SSA maps for volumetric moisture contents. Both maps tended to overpredict observed RZD, although SSA maps occasionally predicted extremely shallow roots. RZD mapping using measured instead of mapped soil properties showed no improvement for maize but substantial improvement for wheat, particularly from coarse fragments, depth to bedrock, and drainage class. For both crops, the dominant source of uncertainty was the crop-specific maximum rooting depth in the RZD rules. For PAWHC, uncertainty was primarily driven by PTF limitations, with bulk density also contributing. These findings highlight the need to refine crop-specific effective maximum rooting depth, calibrate PTFs, and improve soil property maps to produce reliable RZD and RZ-PAWHC maps for crop modeling and agricultural planning in central Ethiopia.

**Keywords:** root zone depth, plant-available water holding capacity, pedotransfer functions, validation, central Ethiopia

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# Characterisation of global and continental DSM products: beyond point accuracy and towards user needs

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**ABSTRACT**

Digital Soil mapping (DSM) at continental and global scale provides standardised global information layers. These layers can be useful to create soil information layers for areas for which local soil survey information is lacking. The recent availability of global and continental remote sensing-derived products coupled with the ease-of-access to computational resources has made the production of such layers, at increasingly higher resolution, easier. Therefore, it is ever more important to characterise and evaluate such DSM-derived products, in particular the type of actual information they can provide to users, that is, their fitness-for-intended-uses.

DSM studies commonly assess prediction uncertainty using various approaches, including multiple simulations or quantile random forests. These studies provide measures of accuracy derived from statistical (cross-)validation, often based on non-probability and non-representative observations. However, these accuracy metrics and uncertainty assessments do not encompass all the potential elements that could be used to characterise a DSM product, nor do they directly address user needs. In this study, we assessed maps based on area of applicability (i.e., the area in covariate space where the model learns about relationships based on the training data), the landscape heterogeneity both in the landscape itself and in covariate space, and the local influence of the covariates on the final products.

We present examples of continental and global mapping products, highlighting main accuracy, uncertainty and interpretability aspects and how these influence their suitability for intended use by stakeholders, decision makers and users in general at the given resolution. The results permit some practical reflections on how to integrate all the above elements to identify regions where the confidence in the predictions – for various intended uses -- is highest and the associated uncertainty lowest, and, conversely, where the product is not considered fit for use.

# Beyond uncertainties: making standalone metrics decision-oriented through game theory

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**ABSTRACT**

Digital soil mapping and its associated uncertainties are communicated through accuracy metrics, confidence intervals, or taxonomic uncertainty maps that have limited relevance to end users. While these measures are essential for scientific transparency, they rarely translate into actionable information for decision-making. As a result, uncertainty often functions as an academic requirement for publication rather than a practical decision-support variable and is frequently overlooked outside specialist communities.

This disconnect reflects a broader limitation in digital soil mapping: uncertainty is typically treated as an endpoint rather than as information that can actively inform land-use choices. Here, we argue that uncertainty can be made functionally meaningful by reframing soil information within a game-theoretic decision framework. Game theory provides a well-established language for decision-making under incomplete information, where actors select strategies based on both expected outcomes and associated risks. Within this framework, soil maps are not static predictions, but information structures that shape rational decisions under uncertainty.

By jointly mapping spatial patterns, such as pedodiversity or other spatial patterns, and predictive uncertainty, soil information is transformed from a descriptive output into a strategic decision surface. In this representation, pedodiversity reflects the potential magnitude and diversity of ecosystem services, while uncertainty quantifies information asymmetry and risk associated with those potential outcomes. This bivariate mapping is formally analogous to a Bayesian game, in which land-use actors operate under incomplete information and ecosystem services act as spatially variable payoffs.

Distinct regions of this decision surface acquire clear interpretive meaning. Areas characterized by high pedodiversity and low uncertainty correspond to dominant or low-risk strategies, where ecosystem service potential is both high and reliable. In contrast, areas with high pedodiversity and high uncertainty represent high-reward but risk-sensitive options, where management actions may yield substantial benefits but also carry greater potential for unintended consequences. Regions of low pedodiversity indicate more limited strategic options, regardless of uncertainty. These distinctions are difficult to infer from spatial patterns or uncertainty maps alone but emerge naturally when combined.

By embedding uncertainty within a game-theoretic interpretation, digital soil mapping moves beyond accuracy-driven evaluation toward transparent, intuitive, and policy-relevant communication. This approach enables soil information to support rational, risk-aware land-use planning and governance, encouraging broader engagement with uncertainty as a guide for sustainable decision-making rather than as an isolated statistical metric.

# From Legacy Soil Maps to Fit-for-Use DSM Products: A Case Study from Portugal

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## ABSTRACT

Operational Digital Soil Mapping (DSM) increasingly underpins land management, environmental policy and sustainability assessments. Yet its effective use is often constrained by outdated, heterogeneous or low functional relevance data. This study presents a reproducible and operational workflow to update and harmonise soil mapping in mainland Portugal at a 1:100,000 scale and using the WRB system, explicitly addressing the fitness for use of DSM products derived from legacy soil data.

Portugal provides a representative case where existing soil maps are inconsistent in classification systems (Soil Classification of Portugal vs. WRB), scales (1:25,000 vs. 1:100,000), and survey and mapping methodologies. In addition, the legacy 1:25,000-scale soil maps lack detailed characterizations for most soil units, and those that are characterized are often incomplete. Rather than relying on data-intensive predictive modelling, the proposed approach uses combinations of soil-forming factors (climate, lithology, and relief) to delineate homogeneous land units that frame and enable the reinterpretation of the 1:25,000-scale legacy soil maps. Within this framework, and considering three study areas (~300,000 ha each): (i) legacy soil profiles were compiled, validated, and harmonised; (ii) soil units were systematically converted to WRB References Soil Groups and qualifiers; (iii) provisional land units were refined to improve internal consistency; (iv) soil mapping units were operationally defined by identifying dominant, co-dominant, and associated soils in each refined land unit.

The resulting soil mapping units were quantitatively validated against 165 legacy soil profiles using a presence/absence scoring method, achieving 76–82% correspondence. This level of validation directly supports the fitness for use of the DSM products and strengthens their credibility for land management and planning applications. Results also demonstrate that lithology emerges as the primary driver of References Soil Group distribution under Mediterranean conditions, while relief and climate refine the spatial variability of key WRB qualifiers linked to soil depth, texture, cation exchange capacity, carbonates and soluble salts content, drainage conditions, water storage capacity, acidity and organic matter status. Despite being produced at a smaller scale, the updated and harmonised 1:100,000 soil map delivers more functionally relevant and interoperable soil information than legacy 1:25,000 maps.

The study explicitly highlights common DSM pitfalls—overreliance on sparse legacy data, opaque classification conversions, and limited validation—and demonstrates how a process-based and pedologically interpretable workflow can mitigate these risks. By prioritising operational robustness, reproducibility and clear validation over methodological novelty, this work provides a practical pathway for producing fit-for-purpose DSM products in data-scarce regions, supporting land evaluation, soil management and evidence-based decision-making at national and European scales.

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# Transposability of MUSE (French DSM method for the Evaluation of Soil Multifunctionality) to EU scale in the framework of EU-funded Horizon Europe SPADES project

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**ABSTRACT**

As part of the Soil Monitoring and Resilience Directive, published on 12 November 2025, the EU parliament has emphasized the importance of setting measures for Union-wide harmonised monitoring and assessment of, and support for, soil health and soil resilience and tackling contaminated sites, in order to achieve healthy soils by 2050. Soil health is known as the continued capacity of soil to function as a vital living system within an ecosystem and land-use boundaries, sustaining biological productivity, maintaining or enhancing air and water quality, and promoting plant, animal, and human health *(Laishram et al., 2012)*. Recognizing this vital role, soil health has become a key parameter to assess, and several methods and tools have been developed for this purpose.

Among them, the MUSE method - originally a French acronym for *Method for the Evaluation of Soil Multifunctionality* - is a Digital Soil Mapping (DSM) approach that evaluates four soil ecological functions: carbon storage, biodiversity storage, infiltration capacity, and agronomic potential *(Branchu et al., 2021).* These functions are assessed individually and in combination through a scoring system that enables the spatialization of results and the evaluation of soil multifunctionality. The outputs of the MUSE method support the assessment of soil health and the guidance of soil management practices by promoting informed decision - making aimed at preserving soil functions, improving soil quality, and ensuring sustainable land-use practices.

The EU - funded Horizon Europe SPADES *(Spatial Planning and Design with Soil)* project aims to integrate soil health into spatial planning and design. By promoting soil literacy and gathering adaptable tools, methods and instruments among the countries involved in the project, SPADES is putting soil health at the heart of planning for the benefit of current and future generations.

Within the SPADES framework, this study seeks to advance the MUSE approach as both Digital Soil Mapping and a decision - support tool for soil health - inclusive land - use management and spatial planning on the European scale. To this end, the work evaluates the method's interoperability across diverse contexts, identifies and addresses barriers to its transposability, and tackles key challenges related to MUSE development and operationalization, including data availability, accuracy, reliability, practical usefulness, interpretability, and the scales "local versus global" transferability issue.

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# Digital Soil Mapping of pH at European scale: comparing national vs. continental inputs

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## ABSTRACT

Soil property mapping at the European scale currently relies on the Land Use/Cover Area (LUCAS) soil survey managed by the Joint Research Centre (JRC). Many Member States (MS) also maintain national soil information monitoring system (N-SIMS) that typically provide higher sampling densities. Technical issues such as harmonization of soil data points and covariates and legal issues such as constraints in sharing coordinates have hindered the integration of national soil information into Eu- wide mapping.
This study evaluates the influence of alternative digital soil mapping strategies on soil pH predictions, using different combinations of European-wide and national datasets in terms of both soil point observations and covariates. Predictive performance, spatial patterns, and cross-border coherence were assessed.
Six country-driven approaches were implemented independently by participating MS using the same modelling framework: (a) Eu-wide covariates (Eu Cov) with LUCAS data, (b) Eu Cov with N-SIMS, (c) Eu Cov with combined LUCAS and N-SIMS data (CombData), (d) Eu-wide and national covariates (Eu- Nat Cov) with LUCAS, (e) Eu- Nat Cov with N-SIMS, and (f) Eu- Nat Cov with CombData. In addition, two continental approaches were implemented by training a single model at the European scale using Eu-wide covariates with either (g) LUCAS data or (h) CombData (federated approach). The federated approach enables the incorporation of national point data without disclosing their coordinates, encompassing legal constraints.
Results indicate that, in most cases, the use of N-SIMS data improved model performance relative to LUCAS, as measured by RMSE, CCC, and MEC, with few exceptions.The use of CombData generally resulted in intermediate performance, often degrading the metrics achieved by N-SIMS alone. The inclusion of Nat Cov consistently enhanced model performance. Among continental approaches, the CombData model outperformed the LUCAS-only model across all evaluation metrics.
At the European scale, spatial patterns were broadly comparable; however, LUCAS-based maps tended to smooth extreme pH values captured by N-SIMS-based models. Substantial local discrepancies (up to 1.8 pH units) were observed between LUCAS and N-SIMS predictions, while N-SIMS and CombData maps showed high spatial consistency. Border artefacts were evident in all country-driven models but were fully eliminated in continental approaches.
Strengths and limitations of the tested approaches are discussed, highlighting the potential of integrating N-SIMS data into Eu-Scale mapping.

# National soil information grids of China: problems and possible solutions

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**ABSTRACT**

Soil information has traditionally been presented as polygon maps at coarse scales. Solving global and local issues, including food security, water regulation, land degradation, and climate change requires higher quality, more consistent and detailed soil information. Accurate prediction of soil variation over large and complex areas with limited samples remains a challenge, which is especially significant for China due to its vast land area which contains the most diverse soil landscapes in the world. Based on almost 6000 soil profiles collected from a recent national soil survey and a suite of detailed environmental covariates, we integrated predictive soil mapping paradigm with adaptive depth function fitting, state-of-the-art ensemble machine learning and high-resolution soil-forming environment characterization in a high-performance parallel computing environment to generate 90 m resolution national gridded maps of soil types and basic soil properties (soil types, pH, organic carbon, sand, silt, clay, nitrogen, phosphorus, potassium, cation exchange capacity, bulk density, coarse fragments, thickness and colours) at multiple depths across China. Then, we used a set of pedotransfer functions and models to predict spatial variations of soil function (hydraulic, thermal, ecological, etc) properties. This study developed high resolution National Soil Information Grids of China as an alternative to the existing out-of-date, spatially-coarse national soil maps and also quantified spatial uncertainty of the digital soil information products which would be useful for decision-making. The relative importance of soil-forming factors in the predictions varied by specific soil property and depth, suggesting the complexity and non-stationarity of comprehensive multi-factor interactions in shaping soil spatial variations. More importantly, we highlighted the prolems and possible solutions in the soil informtion production and its applications under the conditions of limited samples in the large territory with complex soil landscapes. We also tried to describe the possible prospects can the third National Soil Survey can bring to the enhancement and applications of soil information grids of China.

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# Assessing quality gains from physically supervised harmonic fitting for apparent soil thermal diffusivity estimation.

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**ABSTRACT**

Apparent soil thermal diffusivity between 5 and 10 cm can be estimated at the annual scale from temperature time series at two depths under one dimensional heat conduction [ 1,2]. However, purely statistical first harmonic fits may fail to capture atypical transient episodes, biasing parameter estimates and yielding physically inconsistent amplitude and phase relationships between depths. This work quantifies the impact of an explicit physical supervision and quality assurance scheme on national scale apparent diffusivity estimation in Uruguay. Daily soil temperature maps at 5 and 10 cm were used to build intra annual time series for each pixel and year, and the first annual harmonic was fitted by least squares, using a previously developed gridded soil temperature dataset [3]. A physical coherence domain (*Dphys*) for the harmonic parameter vector was defined by amplitude and phase constraints, and internal consistency metrics were formulated to quantify the mismatch between logarithmic amplitude attenuation and interdepth phase lag, including a symmetric relative discrepancy between diffusivity estimates. Global tolerance thresholds were derived through a Monte Carlo residual bootstrap based on paired daily residuals from in situ series, preserving the joint dependence between depths and filtering physically feasible realizations. Local intra annual flags based on vertical temperature differences and harmonic residuals were used to identify candidate segments for correction. For series showing locally incompatible behaviour, a subset based temporal filtering was applied to recover solutions within *Dphys* while minimizing the exclusion of observations and without forcing the remaining signal. Quality gains are assessed by comparing base and final fits in terms of the fraction of series within *Dphys*, the distributions of internal consistency metrics relative to thresholds, shifts in A, B, C quality classes, and the number of excluded observations. The results show that physical supervision increases feasibility and reduces internal inconsistencies while requiring limited removals for recoverable series.

This framework provides a transparent and scalable quality assurance strategy for generating annual and typical apparent diffusivity products from gridded soil temperature datasets.

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# Landscape-scale Detection of the Spatio-temporal Variations of Soil Total Nitrogen and Its Influencing Factors in a Grassland by Soil Mapping

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**ABSTRACT**

Soil mapping is an effective method for obtaining the spatial distribution of soil properties, and conducting soil mapping across different periods can help identify dynamic changes in soils. Existing soil mapping studies have often been carried out at either small scales, such as the plot scale, or large scales, such as the regional and even global scale, while landscape-scale mapping has remained relatively less implemented. The landscape scale is crucial because it can effectively integrate multiple natural and anthropogenic driving factors, providing a key perspective for understanding soil property dynamics under complex interactions. In this study, landscape-scale mapping of topsoil total nitrogen (TN) in the typical temperate grassland of Xilingele was performed for 2014 and 2021 based on revisited sampling, in order to determine the spatio-temporal variation of TN and its dominant driving factors. The spatio-temporal variations of TN at 0–1 cm and 1–6 cm depths in a temperate grassland are identified to analyze the governing processes and identify the major contributing factors. The results showed that TN content exhibited a significant decreasing trend in the study area, with reductions of 0.043% at 0–1 cm and 0.012% at 1–6 cm depth. TN exhibited moderate spatial autocorrelation in both 2014 and 2021, and spatial variability increased at 1–6 cm as the nugget-to-sill ratio rose and range decreased. Higher elevations showed less TN loss than lower elevations, and leeward slopes experienced more substantial TN reduction than windward slopes. Higher land-use intensity correlated with more TN reduction, while long-term ungrazing or markedly reduced intensity lessened it. A wind erosion hotspot identified at a local peak showed less TN reduction, likely due to low land-use intensity and high vegetation cover at high altitude, which mitigated the impacts of wind erosion on TN variation. This study demonstrates that landscape-scale mapping can effectively detect the variation patterns and key drivers of TN. Such information is often overlooked at the field or regional scale. The approach thus enhances comprehensive understanding of the processes driving TN dynamics across the landscape and provides a reliable way to identify dynamic processes in soil-landscape systems.

# Revealing the landscape with Digital Soil Mapping

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**ABSTRACT**

When map users are confronted with a digital soil map (DSM), they do not recognize the traditional polygons delineating soil landscape segments. Rather, they see individual grid cell predictions, with no clear boundaries and often a fine pattern of predicted values. Further, DSM produces a separate map for each soil property at each depth slice. This is useful for modelers, but not for communicating with map users who conceive of, and use, soils as landscape elements recognizable as geomorphic or land use features. In this presentation, we discuss ways to extract meaningful landscape elements from DSM. One solution is to map soil classes, either from original training points or constructed from sets of soil property maps. These are holistic expressions of soil properties and functions and have long been used for communication with land users, especially for technology transfer. Further, soil classes are usually defined in relation to mappable landscape elements. These maps can then be aggregated into polygons at large scales or segmented into heterogenous associations of soil classes at smaller scales. Another solution is to aggregate (at large scale) or segment (at small scale) sets of properties at various depth slices into groups that are relatively homogeneous (aggregation) or with a defined pattern of heterogeneity (segments). These two methods should reveal landscape features that should be familiar to those who work with soil geography, for example landform facets and vegetation communities linked to soil types. This should make the DSM product more approachable and usable for these users. If the DSM products cannot reveal such features, that calls into question their quality and usefulness.

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# Applying Digital Soil Assessment to Support the Effectiveness Evaluation and Design Optimization of Buffer Strips

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## ABSTRACT

Excess nutrient losses from agricultural fields have become one of the major drivers of freshwater eutrophication. Understanding the spatial distribution of soil nutrients is therefore essential for developing effective mitigation strategies. Digital Soil Mapping (DSM) provides a framework for quantifying soil variability by integrating environmental covariates, field observations, and numerical modeling techniques [1], offering an efficient way to predict soil nutrient dynamics in heterogeneous fields. The primary goal of this study is to apply the Digital Soil Assessment (DSA) approach, utilizing spatial soil information derived from DSM, to evaluate the effectiveness of buffer strips in capturing excess phosphorus (P) from agricultural runoff and to support their optimized design. Within the DSM framework, sampling points were selected using the conditioned Latin hypercube sampling (cLHS) method [2], which applies simulated annealing to capture real-world environmental combinations. Soil samples were collected and analyzed for available P using the Olsen P method. The SCORPAN model [3] was employed to compare regression, machine learning, and spatial statistical models in predicting soil available P distribution and to evaluate the influence of environmental covariates on model performance and interpretability, with a Random Forest (RF) model presented as an example illustrating soil available P prediction across the study area (Fig. 1). These analyses provided quantitative evidence for the effectiveness of buffer strips in mitigating soil phosphorus accumulation and runoff risk, serving as a scientific basis for optimizing buffer strip design and spatial configuration.

This study closely aligns with the conference theme by extracting knowledge from DSM and promoting DSA applications to support sustainable nutrient management and water quality protection, thereby encouraging farmers and policymakers to adopt these evidence-based practices in agricultural management.

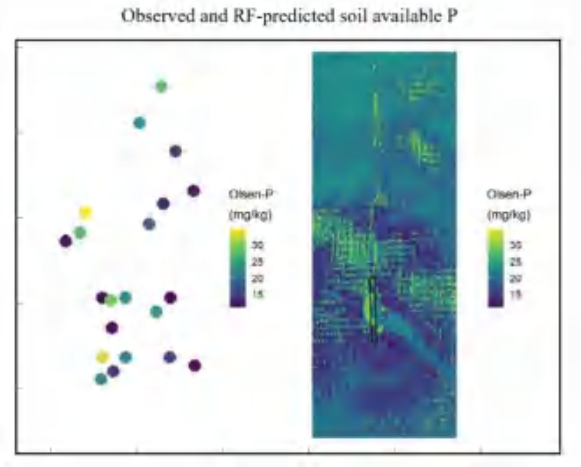



Fig. 1. Observed and predicted distribution of soil available P across the study area.

**Keywords:** Eutrophication, Phosphorus (P), Buffer strips, Digital Soil Mapping (DSM), Digital Soil Assessment (DSA).

**Acknowledgments**

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# Determination of the Cultivated Land Quality Red Line in Northeast China

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## ABSTRACT

The foundation of ensuring national food security lies in cultivated land, with the core being its quality. The Northeast region, as China's most important commercial grain production base, has the sustainable utilization of its cultivated land resources and the guarantee of its production capacity directly related to the overall national food security strategy. However, under multiple pressures such as climate change, intensive utilization, and human management, the sustainability of cultivated land quality and grain production capacity in the Northeast faces severe challenges. Traditional cultivated land protection policies mostly focus on the "quantity red line," while research on the quantitative definition and realization pathways of the "quality red line" remains insufficient. In view of this, this study takes the entire Northeast region and its core grain production units (Heilongjiang Province, Jilin Province, Liaoning Province, and the Eastern Four Leagues of Inner Mongolia) as the research objects. Following the research logic of "evaluation - prediction - correlation - inversion - analysis," and comprehensively utilizing multi-source data and cutting-edge machine learning methods, it aims to scientifically delineate the cultivated land quality red line and key indicator red lines for the Northeast region, and reveal their multi-dimensional driving mechanisms, thereby providing a theoretical basis and decision support for implementing the "storing grain in the land" strategy and precisely improving cultivated land quality.

First, it systematically evaluated the cultivated land quality in the Northeast region and accurately assessed the grain production capacity. Based on the technical specifications for the third national soil survey's cultivated land quality grade evaluation, this study re-evaluated the cultivated land quality of the entire Northeast region and its respective provinces/leagues, obtaining detailed spatial distribution data of cultivated land quality grades. On this basis, to overcome the lag and limitations of traditional statistical data, we constructed a multi-factor integrated grain production capacity assessment and prediction model. The model integrates long-term time series historical yield statistics, high spatiotemporal resolution remote sensing images (such as vegetation indices, leaf area index, etc.), and gridded meteorological data (temperature, precipitation, etc.). Methodologically, we innovatively employed two single models with powerful nonlinear fitting capabilities—BP neural network and random forest—and further utilized an ensemble learning algorithm to combine their strengths, constructing a combined model with stronger robustness and higher prediction accuracy. This model not only enables accurate assessment of historical grain production capacity but, more importantly, allows for reliable prediction of future grain production capacity under different climate scenarios and farming management practices.

Second, it revealed the complex nonlinear relationship between cultivated land quality and grain production capacity. Clarifying the quantitative relationship between the cultivated land quality grade index and grain production capacity is the core scientific issue for delineating the quality red line. This study abandoned simple linear correlation assumptions and employed advanced machine learning interpretability techniques to deeply analyze this black-box relationship. Using the partial dependence analysis provided by the random forest model, we quantified the marginal effects of individual key cultivated land quality indicators (such as soil organic matter, pH, etc.) on grain production capacity, identifying the production capacity thresholds and inflection points for each indicator. Simultaneously, we introduced nonlinear activation functions such as the Sigmoid function from neural networks and successfully constructed a universal nonlinear relationship model from the comprehensive cultivated land quality grade index to grain production capacity. This model clearly delineates the pattern of "quality improvement - production capacity response": in low-quality grade intervals, a slight improvement in quality leads to a rapid increase in production capacity; whereas in high-quality grade intervals, the marginal production capacity benefit of quality inputs diminishes. The establishment of this relationship realizes the scientific transformation from "quality state" to "production capacity output," providing a key bridge for subsequently inferring quality requirements based on production capacity demand.

Third, based on multi-scenario simulations, it scientifically delineated the cultivated land quality red line for the Northeast region and its sub-regions. The delineation of the "red line" must be dynamically linked to future food demand. This study first predicted the future population size, dietary structure changes, and the resulting per capita grain demand in the study area. On this basis, different food security scenarios (e.g., basic subsistence, nutritional well-being, affluent abundance, etc.) were set, and the minimum total grain production capacity required to meet regional food self-sufficiency or specific commercial grain output tasks under each scenario was calculated. Then, we used the aforementioned established "quality-production capacity" nonlinear relationship model for reverse deduction: namely, targeting the guarantee of future grain production capacity demand under specific scenarios, we inverted the minimum cultivated land quality level that must be maintained in each region, i.e., the "cultivated land quality grade red line." Furthermore, based on the key indicator thresholds identified through partial dependence analysis, we further decomposed and transformed the comprehensive grade red line into specific key cultivated land quality indicator red lines (such as soil organic matter content red line, pH range red line, etc.). The research results not only provide a macro red line value for the entire Northeast region but also offer more refined, differentiated red line standards for regions with different physical geography and farming conditions, such as Heilongjiang Province, Jilin Province, Liaoning Province, and the Eastern Four Leagues of Inner Mongolia, achieving "tailored strategies for each location" and precise management and control for cultivated land quality protection.

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# Mapping Spatiotemporal Soil Temperature in Real-time using Neural Networks Combined with Heat Transfer Equation

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**ABSTRACT**

Accurate estimation of soil temperature (ST) dynamics is essential for understanding subsurface heat transfer and its influence on soil processes such as moisture retention, microbial activity, and carbon cycling. However, direct soil temperature measurements are often limited in space and time. This limitation limits the use of machine learning models to extrapolate in space. In this study, we solved the heat transfer equation numerically to estimate daily ST at multiple depths across Tasmania. Governed by soil moisture and soil physical and thermal properties (heat capacity and thermal conductivity), heat was propagated from the surface downward at 10 cm intervals to 1 m depth using a stable finite difference approach. Validation against in-situ observations from multiple sites showed strong agreement in capturing seasonal temperature fluctuations, with reduced error at deeper layers. Land surface temperature modelling using neural networks with land-cover further improved the model. This study demonstrates that finite difference combined with neural networks models can effectively characterize soil thermal regimes with minimal inputs, supporting dynamic soil temperature mapping and integration into process-based soil and carbon models.

**Keywords:** soil temperature, soil thermal properties, finite difference method, process-based models

# New dimensions of farmers' decision making: Demonstration of a 3D web-viewer for erosion mitigation strategies

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**ABSTRACT**

Erosion mitigation strategies in agriculture are crucial for preserving soil functions, vital aquatic ecosystems and related ecosystem services. However, due to limited capacities among agricultural advisory services, farmers often do not receive adequate guidance. To address this gap, the Digital Agricultural Knowledge and Information System (DAKIS) aims to support farmers in planning and implementing mitigation strategies on individual sites. Within the project, digital and automated tools have been developed to calculate high resolution (1 meter) erosion rasters, erosion hotspots and potential sites for in-field raised vegetative barriers (beetle banks). This study examines: i) how to provide the given tools' results in a user-friendly format, ii) how to raise awareness of sub-field erosion risks, and iii) how to support farmers in implementing effective erosion mitigation strategies.

The study area is a watershed (ca. 15 km³) in southern Germany (Bavaria) characterized by a hilly topography and occasional heavy rainfall events leading to high erosion. The automated tools are applied, and the results are integrated into a public, web-based, 3D viewer (EROSPOT 3D). It allows for an interactive visualization and exploration of a three-dimensional landscape using a digital elevation model (Figure 1). Erosion risks are visualized using a traffic light color scheme ranging from low (green) to high (red), while delineated erosion hotspots are shown as clickable 3D objects (red) that provide quantitative information on annual soil loss. Potential sites for beetle banks are also shown as clickable 3D objects (green) that provide information about potential subsidies. The visualized 3D landscape is supplemented by a dataset showing runoff paths and water bodies (blue).

EROSPOT 3D illustrates the relationships between terrain, runoff, erosion, and connectivity to aquatic ecosystems while potential mitigation strategies are provided. Therefore, it reduces the need for physical meetings between advisors and farmers, as on-site knowledge, for instance about terrain characteristics and related runoff pathways, is provided online. Unlike 2D maps, terrain-based processes leading to erosion and the relevance of mitigation strategies, such as vegetation buffers along valley paths or beetle banks across slopes, are more comprehensible, which may improve farmers' understanding and acceptance of these strategies. Additional functions could be added to the 3D web-viewer, such as interfaces for downloading and transferring data, including spatial information on the position of beetle banks to enable exact on-site implementation as part of a holistic farm management information system for sustainable agriculture on sloping farmland.



Figure 1: EROSPOT web-app, online available via: www.erospot.de

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# Continental-Scale Soil Assessment in Africa: Design, Implementation, and Early Findings from Soils4Africa

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**ABSTRACT**

Reliable and harmonized soil information remains scarce across Africa, limiting the continent's ability to address soil degradation, strengthen climate-resilient agriculture, and guide evidence-based land management. The Soils4Africa project implemented a coordinated, continental-scale field campaign across 33 countries to establish a standardized soil information baseline for agricultural lands. Using a hierarchical probabilistic sampling design, the campaign collected more than 25,000 soil samples and extensive field observations between 2022 and 2025, representing 80% of the planned coverage. Operational constraints, including restricted access to private estates, security risks, and severe seasonal flooding, prevented sampling in 21% of targeted locations, providing important lessons for future monitoring frameworks. Field observations revealed that African agricultural landscapes are overwhelmingly open, with more than half of sites exhibiting very sparse vegetation and 21% essentially bare. Tree canopy cover classes were dominated by the Absent and Scattered categories, indicating widespread structural simplification of agroecosystems. Soil physical and morphological properties exhibited high spatial variability, with coarse fragments, compaction, and subsoil rooting barriers commonly observed. Bulk density patterns further reflected regional differences in organic matter status, land use intensity, and parent material. Overall, the results demonstrate significant constraints to soil health linked to vegetation loss, limited fertility inputs, and inadequate soil and water conservation practices. The dataset and protocols developed through Soils4Africa provide a critical foundation for long-term soil monitoring, digital soil mapping, and sustainable land management planning across Africa.

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# Mapping of bundles of soil-based ecosystem services in the European Union and their evolution by 2050

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**ABSTRACT**

Soil health can be assessed by the extent in which the soil is able to provide various ecosystem services. Ecosystem services are the direct and indirect contributions of an ecosystem to human well-being. The ecosystem services provided by soils or related to soils are known as soil-based ecosystem services (SESs). SESs are directly and quantifiably controlled by soil chemical, physical and biological properties, processes and functions. SESs do not occur separately in the environment, but simultaneously. They should thus be evaluated together as SESs bundles. In addition, these services are threatened by global changes, such as climate change and changes in land use, which will affect their provision. This work aims to define SESs bundles at the European Union (EU) level, and to evaluate the effect of climate and land use changes on their evolution by 2050. The SESs assessed include hydrological control (HC), soil erosion control (SEC), greenhouse gas and climate regulation (GHG), and primary biomass production (PBP). To assess HC, the digital soil mapping approach was used. SEC was quantified through the Revised Universal Soil Loss Equation (RUSLE). For GHG and PBP, dynamic global vegetation models (DGVMs) produced by UK Earth System Models (UKESM) were exploited. The impacts of climate change were assessed using two Shared Socioeconomic Pathways (SSP1-2.6: sustainable scenario, and SSP5-8.5: high-emission scenario with significant climate impacts). Concerning land use change, we used the projections provided by the LUISA (Land Use-based Integrated Sustainability Assessment) modelling platform. The assessment offers a comprehensive analysis of the spatial distribution and projections for the SESs bundles in the current state and by 2050. Clustering methods, specifically k-means, were employed to identify SESs bundles at EU scale. The proposed approach allowed us to identify hotspots with high or low provisions of a set of SESs and how these sets will be evolved by 2050 under the pressure of climate and land use change. Moreover, it could provide guidance for sustainable agriculture in the framework of the EU Green Deal and the Soil Strategy for 2050.

**Acknowledgments**

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# Intelligent Mapping Paradigm to Overcome Systematic Bias in Remote Sensing SOC Estimation: A Case Study of the Black Soil Region in China and the United States

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**ABSTRACT**

Soil organic carbon (SOC) is a crucial indicator for maintaining soil fertility and regulating carbon balance in black soil regions. However, its strong spatial heterogeneity and the limited capacity of remote sensing feature extraction often lead to systematic mapping errors, typically manifested as the underestimation of high values and overestimation of low values. To address this issue, we propose an SOC mapping framework that integrates prior geographic knowledge with deep learning, and develop a GMM-AG-CNNLSTM model incorporating fuzzy clustering and spatiotemporal feature extraction. The framework was applied to typical black soil regions in Northeast China and North America. A total of 2,616 surface SOC samples (0–20 cm) were compiled to build a multi-source spatiotemporal feature set. The approach first employs a Gaussian mixture model (GMM) to partition SOC levels and mitigate prediction bias caused by spatial heterogeneity. Subsequently, a weighted attention mechanism, convolutional neural networks (CNN), and long short-term memory (LSTM) networks are combined to achieve deep spatiotemporal feature fusion and generate SOC distribution maps at a 30 m resolution. Results demonstrate that the GMM-AG-CNNLSTM model achieved prediction accuracies of $R^2$=0.73/RMSE=5.42 g/kg in Northeast China and $R^2$=0.70/RMSE=5.89 g/kg in North America, outperforming random forest and conventional deep learning models, with greater stability in both high- and low-SOC regions. Spatial analysis further revealed that SOC in Northeast China exhibited higher mean values and a larger proportion of high-value areas compared with North America, though with a wider distribution of low-value areas. This study presents a high-accuracy SOC remote sensing mapping method that can provide valuable support for carbon sequestration assessment and degradation monitoring in black soil regions.

**Keywords:** Soil organic carbon, Deep Learning, GMM-AG-CNNLSTM Model, Spatial Heterogeneity, Carbon Sequestration

# Spatial Variability of Soil Acidity and Mapping of Selected Soil Properties in Chancho Micro Watershed, South western Ethiopia

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**ABSTRACT**

The study was conducted to evaluate the spatial variability in soil acidity and mapping of selected soil properties in Chancho micro Watershed, Gechi District South Western Ethiopia. A total of 41 geo–Referencesd composite soil samples were collected from cultivated land using a random grid survey method at a depth of 20 cm for annual crops and 50 cm for perennial crops from surface soil of cultivated land. Selected soil property maps were developed using spatial prediction of semivariograms and the ordinary kriging interpolation technique using Arc-GIS.The pH of the soil was varied from extremely acidic (4.32) to strongly acidic (5.28). The values of exchangeable acidity and exchangeable aluminum were ranged from (0.26 to 2.3cmolckg-1and (0 to 1.87 cmolckg-1), respectively. Available phosphorus stretched from 0.45 to 1.88 mgkg-1, which is low to very low level whereas, optimum to low level organic carbon value that ranged from 1.06 to 3.93% was recorded. Furthermore, high to low levels of exchangeable calcium ranged from 13.12 to 5.05 cmolckg-1 was observed. The finding indicated that deficiency of available phosphorus, organic carbon, total nitrogen, and exchangeable calcium were the major limiting factors of acidic soil of study area. Thus, digital soil mapping produced for this study was important to address spatial variability of soil acidity and nutrient status in agricultural lands. Consequently, it is basic for efficient nutrient management, advisory work and decision makers to enhance site specific soil acidity management.

**Keywords:** Arc-GIS, Ordinary kriging, soil characterization, soil mapping and watershed

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# Assessing the carbon sequestration potential and identifying influential factors of cultivated soils in Northeast China

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**ABSTRACT**

Cultivated lands play a crucial role in terrestrial carbon cycle, and enhancing soil organic carbon (SOC) sequestration in these areas can help effectively mitigate the rise of atmospheric $CO_2$ concentration. In this study, topsoil (0-20 cm) saturated SOC and its density of cultivated soil in Northeast China were mapped using a boosted regression trees (BRT) model. The distribution of the SOC sequestration potential was also calculated
based on the difference between saturated SOC and SOC density in ArcGIS. Nine environmental factors including climate, topography and lengths of cultivation data (LCD) and 197 soil samples are used. A 10-fold crossvalidation technique is applied to derive four statistical indices - mean absolute prediction error (MAE), root mean square error (RMSE), coefficient of determination ($R^2$) and Lin's consistent correlation coefficient (LCCC) to verify the model performance. The model explains 81% and 85% of the spatial variation of saturated SOC and SOC density, respectively. Mean annual temperature and mean annual precipitation are key factors controlling SOC density and saturated SOC distribution. In addition, LCD showed a similar spatial pattern to SOC sequestration potential, influencing the distribution of SOC density and saturated SOC in the study area. We recommend LCD as an important factor to consider in saturated SOC and SOC density predictions, especially in the farmland ecosystem with a long reclamation history. Accurate mapping SOC sequestration potential and identifying environmental factors will help manage land use and promote soil quality evaluation and improve soil carbon sequestration in this region.

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# Three-dimensional soil organic carbon stocks in Tibet, China: spatial heterogeneity, driving factors, and future Changes

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**ABSTRACT**

Understanding the spatiotemporal distribution of soil organic carbon (SOC) stocks enables a critical assessment of terrestrial carbon sequestration potential and supports the formulation of effective climate mitigation policies.However, the prevailing emphasis on surface soil layers in SOC research has neglected the full three-dimensional distribution of stocks, its spatial heterogeneity, and the primary controls on subsurface carbon accumulation. Consequently, we developed a novel hybrid framework integrating equal-area spline functions, boosted regression trees (BRT), and a space-for-time substitution method. This approach was applied to quantify the vertical profile of SOC stocks in Tibet and project their dynamics under future climate warming scenarios. To this end, a dataset comprising 105 soil profiles and nine environmental covariates (climatic, topographic, and anthropogenic) was utilized to calibrate and validate the BRT model, which involved a 10-fold cross-validation procedure. The model exhibited robust predictive accuracy, with low MAE and RMSE alongside high $R^2$ and LCCC values. Spatially, SOC stocks were predicted to be highest in the southeast and lowest in the northwest, a pattern corresponding to grassland ecosystems storing the largest carbon pool. Over 47% of this pool was concentrated in the upper 30 cm. Projections under 1.5 °C, 2 °C, and 4 °C warming scenarios indicated total SOC stocks (0–1 m) would decrease by 0.43%, 0.60%, and 1.40%, respectively. The three-dimensional variability of SOC stocks was primarily controlled by mean annual precipitation, slope gradient, and slope aspect—insights that pave the way for high-resolution three-dimensional mapping under different climate scenarios and directly support the development of adaptive land management strategies for improved carbon governance.

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# Soil organic carbon in Chinese grassland ecosystems: spatial heterogeneity, driving factors, and future changes

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**ABSTRACT**

Soil organic carbon (SOC), a critical component of the carbon pool in grassland ecosystems, playes a vital role in maintaining soil fertility, regulating carbon cycling, and responding to climate change. This study developed boosted regression tree (BRT) and random forest (RF) predictive models based on SOC data collected from 688 grassland sites across China in 2018, along with eight terrain and climate-related environmental variables. Through 10-fold cross-validation and evaluation using four performance metrics—R2, Lin's concordance correlation coefficient, mean absolute error, and root mean square error—the BRT model was found to outperform the RF model in terms of prediction accuracy and consistency, with significantly lower errors. The key environmental drivers influencing SOC distribution were identified as annual mean precipitation, elevation, and annual mean temperature. Based on these findings, the "space-for-time" substitution approach was applied, and the BRT model was used to project spatial changes in grassland SOC across China in the 2050s and 2090s under two future climate scenarios (SSP245 and SSP585). Results indicate that by the 2050s, SOC content is projected to decrease by 5.3 g kg-1 under the SSP245 scenario and by 5.8 g kg-1 under the SSP585 scenario compared to 2018 levels. By the 2090s, the decline under SSP245 is expected to reach 6.6 g kg-1, while under SSP585 it will reach 8.5 g kg-1. The high-resolution SOC content spatial data and projections generated in this study provide valuable scientific support for climate change adaptation strategies in China's grassland ecosystems, contributing to sustainable soil management and ecological restoration efforts..

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# Spatio-Temporal Variations in Soil Organic Carbon Stocks in Different Erosion Zones of Cultivated Land in Northeast China Under Future Climate Change Conditions

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**ABSTRACT**

Soil organic carbon (SOC) plays a critical role in the global carbon cycle and serves as a sensitive indicator of climate change impacts, with its dynamics significantly influencing regional ecological security and sustainable development. This study focuses on the Songnen Plain in Northeast China—a key black soil agricultural region increasingly affected by water erosion, primarily through surface runoff and rill formation on gently sloping cultivated land. We aim to investigate the spatiotemporal dynamics of SOC stocks across different cultivated land erosion zones under projected future climate change scenarios. To quantify current and future SOC stocks, we applied a boosted regression tree (BRT) model based on 130 topsoil samples (0–30cm) and eight environmental variables representing topographic and climatic conditions. The model demonstrated strong predictive performance through 10-fold cross-validation, yielding high $R^2$ and Lin's concordance correlation coefficient (LCCC) values, as well as low mean absolute error (MAE) and root mean square error (RMSE). Key drivers of SOC stock spatial variation were identified as mean annual temperature, elevation, and slope aspect. Using a space-for-time substitution approach, we projected SOC stocks under the SSP245 and SSP585 climate scenarios for the 2050s and 2090s. Results indicate a decline of 177.66 Tg C (SSP245) and 186.44 Tg C (SSP585) by the 2050s relative to 2023 levels. By the 2090s, SOC losses under SSP245 and SSP585 are projected to reach 2.84% and 1.41%, respectively, highlighting divergent carbon dynamics under varying emission pathways. Spatially, SOC stocks were predominantly located in areas of slight (67%) and light (22%) water erosion, underscoring the linkage between erosion intensity and carbon distribution. This study underscores the importance of incorporating both climate and anthropogenic influences in SOC assessments. The resulting high-resolution SOC distribution map provides a scientific basis for targeted ecological restoration, black soil conservation, and sustainable land management in the Songnen Plain, thereby supporting regional climate resilience and China's "dual carbon" goals. These insights also contribute to global efforts in enhancing soil carbon sequestration and achieving carbon neutrality goals.

**Keywords:** soil organic carbon stocks; water erosion; geospatial machine learning; climate change scenarios.

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# Digital mapping of Solonetz within forest-steppe landscapes of the Oka-Don Lowland

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**ABSTRACT**

Chernozems dominate the flat, poorly drained interfluves of the Oka-Don Lowland under conditions of shallow groundwater. The landscape is characterized by numerous shallow flat depressions, where Solonetzes develop due to a pulsating hydrological regime, saline parent materials, and mineralized groundwater close to the surface. This area represents one of the northernmost occurrences of Solonetz worldwide. High heterogeneity of vegetation cover and microrelief complicates prediction of Solonetz distribution using digital soil mapping (DSM). The aim of this study was to develop an approach for mapping Solonetz in forest-steppe landscapes of the Oka-Don Lowland using DSM techniques. The study was conducted at a key site (8.4 km²) in the southern Oka-Don Lowland. The dataset included 95 soil profiles, topography and vegetation covariates derived from Sentinel-1 and Sentinel-2. Soil description and classification followed the WRB system. Soil distribution was modeled using the Random Forest method at a spatial resolution of 10 m.

The resulting soil map shows that Calcic Gleyic Solonetz (Clayic, Aric) and Calcic Gleyic Solonetz (Clayic) occupy slightly concave, elongated depressions and cover about one quarter of the study area. Convex landforms are dominated by Dry Calcic Chernozem (Aric, Clayic) and Calcic Gleyic Chernozem (Aric, Clayic), accounting for nearly half of the area. Larger depressions are characterized by Planosols, Stagnosols, and Gleysols, while undisturbed Calcic Gleyic Chernozems occur mainly along depression margins.

The most important predictors were closed depressions and TPI layers derived from the DEM, and NDVI. These layers were contributed most to model performance. Vegetation types were predicted with optical and SAR data improved discrimination between woody vegetation, meadows, and agricultural fields.

The overall map accuracy reached 75%. Solonetz soils had the lowest accuracy due to complex spatial positions, occurring in shallow depressions within fields with xerophytic vegetation. Its classification improved Solonetz detection by 10–15%. Chernozems were predicted with highest accuracy, supported by more sampling points and association with agricultural fields. Soils in deeper depressions were mapped less precisely.

DSM delineated forest-steppe soils on undrained interfluves and in closed depressions (Solonetz). The accuracy of soil determination strongly depended on the integration of multisource remote sensing data, terrain and vegetation indices, enhancing detection of Solonetz in fields and deeper depressions.

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# Comparative Study on Soil Spatial Provenance Based on Soil Property Similarity Clustering and Pedogenic Environment Inference

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**ABSTRACT**

Soil spatial traceability has significant application value in forensic soil science and judicial identification. This study, based on 265 surface soil samples from Anhui Province, compares two soil provenance strategies: (1) a similarity-matching and spatial clustering approach, which filters similar samples using spectral and physicochemical property similarities and applies the DBSCAN algorithm to determine the potential source area of unknown samples; (2) an inverse inference approach based on pedogenic environmental factors, which employs a random forest model to predict environmental variables such as soil parent material, land use, topography, climate, and vegetation, and infers provenance by integrating spatial distribution maps. By simulating provenance analysis, the accuracy and applicability of the two strategies are evaluated. The results indicate that the similarity-matching strategy achieves higher localization accuracy under conditions of strong spatial proximity and well-established databases, while the inverse pedogenic environment inference strategy demonstrates superior spatial constraint capabilities in regions with limited databases or strong spatial heterogeneity. Each strategy has its own advantages, and their integrated application holds promise for further improving the accuracy and resolution of soil spatial provenance analysis.

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# Integrating Hierarchical Factor Analysis and Digital Soil Mapping to Update Legacy Maps and Identify Soil Carbon Loss Hotspots for Land-Use Policy

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## ABSTRACT

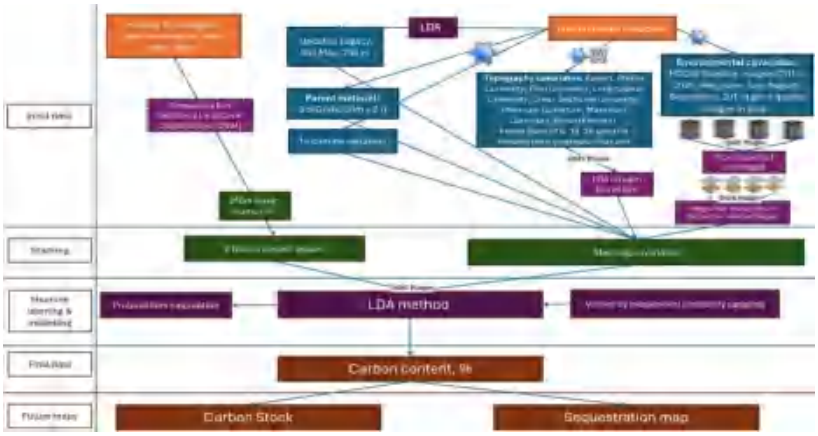
Accurate spatial data on soil organic carbon (SOC) stocks as well as degradation and climate risks are indispensable for informing national climate strategies and the implementation of Nature-Based Solutions (NBS). This study demonstrates a scalable and cost-effective digital soil mapping (DSM) approach to update legacy soil information and model SOC stock and dynamics, with a specific focus on identifying carbon loss hotspots for policymakers. The methodological framework could be applied within the NBS digital platform for planning land restoration activities such as a platform developed by the Centre of Digital Technologies for NBS at HSE University.

DSM approach (Picture 1) tested on the arable lands of the Republic of Tatarstan (4.5 M ha), integrates the national 1:2.5M scale legacy soil map with a multi-source predictors system. This system employs Hierarchical Factor Analysis on multi-annual MODIS satellite imagery (2013–2025) to derive invariant soil and landscape states, representing integral gradients of productivity, thermal, and moisture regimes, alongside morphometric variables. While Linear Discriminant Analysis (LDA) was selected for modeling due to its interpretability, deriving a linear decision boundary defined by coefficients directly linked to predictor contributions, other algorithms, such as Random Forest and Neural Networks, were also tested showing comparable accuracy results. Model performance is quantified using a contingency matrix, from which overall accuracy and weighted and unweighted Cohen's kappa is derived. This assessment allows for the iterative refinement of the predictor set or the class structure if necessary. Trained on generalized soil classes from the legacy map and complemented with field-level SOC content data, the LDA model generated a refined, pixel-level predictive soil map with more than 60% overall accuracy tested on independent probability sample.

The resulting 250m resolution soil map and SOC stock map serve as environmental covariates. Within the NBS platform, they facilitate the enhancement of national-scale SOC stock models (e.g., Romanenkov et al., 2024). By integrating this updated pedological basis with dynamic data on land use and management practices, the platform can model SOC sequestration potential and, conversely, delineate areas at high risk of carbon loss, identified as hotspots. The presented DSM approach provides a reproducible and resource-efficient tool with probabilistic translations, offering policymakers a robust, data-driven foundation for targeting conservation efforts and monitoring the efficacy of land management policies across regions.

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**Picture 1.** Modelling process design.

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# Spatially-Explicit Uncertainty and Feature Attribution in Landscape-Scale Topsoil Carbon Mapping in Forest-Steppe

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**ABSTRACT**

Forest-steppe landscapes exhibit pronounced soil organic carbon (SOC) variability formed by biotope mosaics, yet spatial uncertainty patterns remain poorly characterized. This study combines topsoil (0-15 cm) SOC mapping with spatially-explicit uncertainty and feature attribution analysis in the Oka-Don Lowland forest-steppe (Tambov Region, Russia). We collected 413 samples using representative sampling and verified predictions at 42 locations across meadow-cropland, meadow-forest, and cropland-forest transitions.

Predictors included UAV-LiDAR micro-topography (2 m), multi-year Sentinel-2 phenology, vegetation/moisture indices, and ground-sampled pH. We compared hybrid CNN-LSTM-MLP model that processes spatial patches, temporal sequences, and tabular features against CatBoost, Cubist/SVR, and PLSR using spatially clustered cross-validation. Uncertainty was quantified via 1000-iteration bootstrap with prediction interval range (PIR) mapping.

CNN-LSTM-MLP achieved highest accuracy ($R^2$ = 0.67, RMSE = 5.8 g $kg^{-1}$) with narrowest PIR (23 g $kg^{-1}$), outperforming CatBoost ($R^2$ = 0.61) and PLSR ($R^2$ = 0.42). Spatial uncertainty mapping revealed 40-50% higher PIR in ecotones versus biotope interiors, with meadow-forest transitions showing maximum uncertainty (PIR = 35 g $kg^{-1}$).

Spatially-explicit SHAP (SHapley Additive exPlanations) analysis [1] revealed difference in feature importances between biotopes and ecotones. Forest interiors showed TWI dominance mean SHAP = 0.42, while in ecotones phenological variables had higher importance (EVI2 greenup, mean SHAP = 0.38 in forest-meadow transitions). Spatial SHAP variance mapping identified ecotones as feature importance instability zones.

Cross-model SHAP comparison showed deep learning architectures had 28% lower spatial variance than tree-based methods in homogeneous areas.

Our uncertainty-interpretability framework demonstrates ecotones as uncertainty hotspots requiring targeted sampling for precision carbon accounting. Bootstrap PIR identifies where uncertainty is high; SHAP reveals why through feature attribution instability.

**Acknowledgments**

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# Integrating Digital Soil Mapping and Remote Sensing–Based Soil Moisture for Crop Water Requirement Modelling at the Land Parcel System Scale

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**ABSTRACT**

This study aims to test an integrated methodology based on digital soil mapping techniques to generate spatially distributed data on soil physical and hydrological properties, supporting the assessment of crop irrigation requirements at a detailed spatial scale, such as irrigated parcels within the Land Parcel System. The approach complies with the requirements of the FAO dual crop model (Pereira et al., 2020) and is applied to selected areas in Central and Southern Italy managed by land reclamation consortia.

The data preparation process consists of several steps, moving from coarser to finer spatial scales through downscaling operations. Starting from the national CREA database of soil profiles, first a normalization of the measured basic physical and chemical properties (texture, organic carbon, pH, and bulk density) was carried out using a spline methodology (Bishop et al., 1999) at the FAO References depths: the surface layer (10 cm) and two root-zone depths (70 and 100 cm). The pedological data were then spatialized using a machine learning algorithm (Random Forest) at a 100 m resolution on an INSPIRE sub-grid as a first spatialization step. A set of 16 covariates transformed into raster format, including categorical variables, morphometric variables (DEM and derivatives), and variables derived from remote sensing imagery (Landsat OLI), were used after an appropriate resampling to the working spatial resolution.

Subsequently, the Pedotransfer functions (PTFs) with higher performance tested at the European level and implemented in R (Euptfv2; Szabó et al., 2021) were applied to the dataset to estimate hydrological properties, including: water content at field capacity, wilting point, saturated hydraulic conductivity (Ks, cm/day), and porosity (calculated from bulk density) at the three References depths. In a second step, downscaling to a 10 m resolution was performed in areas classified as irrigated in the Land Parcel System, evaluating and applying the most suitable resampling method (bicubic). To estimate soil moisture dynamics at the three depths, the Soil Moisture Analytical Relationship (SMAR) model (Manfreda et al., 2014) was applied using Sentinel-1 and Sentinel-2 imagery integrated through cloud computing approaches (Faridani et al., 2017). This method was considered the only feasible approach at such a high spatial resolution and pixel density, compared to point-based physically based hydrological models. The results allowed us to track and estimate uncertainties at the various stages, including the spatialization, the application of PTFs, and the SMAR model, using point-based measured datasets—both physical and hydrological—from the national CREA database. Overall, the study demonstrates the feasibility of integrating multiple methodologies and data sources to support assessments at an extremely detailed spatial scale.

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# Model Selection for Digital Soil Mapping Using Spatial Structure Indices

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**ABSTRACT**

The selection of models for digital soil mapping relies on different assumptions regarding the spatial structure of soil properties. Accurately recognizing this structure is therefore critical for selecting appropriate models. However, the potential of spatial structure characterization for guiding model selection in digital soil mapping remains underexplored. This limitation largely stems from the difficulty of quantifying spatial structure when soil observations are sparse and full spatial coverage of the target soil property is unavailable.

In this study, we employ recently developed spatial structure indices derived from limited soil samples and environmental covariates to support model selection in digital soil mapping. A case base comprising 80 soil property prediction scenarios with consistent prediction targets and comparable analytical scales is constructed for evaluation. Two representative model types are analyzed: Ordinary Kriging (OK), representing spatial-autocorrelation-based geostatistical models, and Random Forest (RF), representing covariate-based machine learning models.

The results demonstrate that spatial structural characteristics of the soil–environment system are closely linked to model performance. Based on these characteristics, appropriate model types can be identified with an overall accuracy of 82.9%. These findings indicate that spatial structure indices provide an effective and explainable basis for model selection in digital soil mapping, bridging spatial structure analysis and predictive modeling under sample-limited conditions.

# Enhancing Regional Topsoil Total Nitrogen Mapping through Differentiated Fusion of Ground Hyperspectral Data and Satellite Images Under Low Vegetation Cover

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**ABSTRACT**

Total nitrogen in soil (STN) serves as a crucial indicator of soil nutrient content and provides an essential nitrogen source necessary for crop growth. Precise inversion of STN content is essential for the sustainable use of soil resources and the advancement of agricultural development, particularly to achieve efficient fertilization. However, due to the weak spectral signals of STN and the interference of mixed cropping farmland vegetation cover, achieving high-resolution measurement and precise characterization of STN heterogeneity using satellite remote sensing remains a challenge. In this study, conducted in Zouping City, Shandong Province, we propose a method based on the Differentiated Fusion of Enhanced Multispectral Image Bands (DFE_MSIBs) combined with machine learning algorithms for the spectral inversion of STN content. First, a vegetation-soil spectral unmixing model was applied to reduce the influence of photosynthetic vegetation spectra on soil property spectra under low vegetation cover. Second, we integrated Sentinel-2A multispectral images with ground-based hyperspectral data using Non-negative Matrix Factorization (NMF) to construct the DFE_MSIBs . Finally, we compared the performance of Partial Least Squares Regression (PLSR), Random Forest (RF), and Convolutional Neural Networks (CNN) for STN inversion, incorporating a comprehensive set of predictors including vegetation indices, soil indices, environmental variables, topographic factors, and Sentinel-1 SAR data.The findings demonstrate that the enhanced spectral characteristics and differentiated fusion method not only strengthen the relationship between STN and Sentinel-2A MSI data but also enhance the precision of regional STN inversion models. The DFE_MSIBs method combined with the Random Forest (RF) algorithm yielded the optimal performance, with a Coefficient of Determination $R^2$ of 0.95, Root Mean Square Error (RMSE) of 0.10 g/kg, and Lin's Concordance Correlation Coefficient (LCCC) of 0.89. Compared to the unfused model, the average $R^2$ value increased by 0.02, and the average RMSE decreased by 0.01 g/kg. Additionally, Sentinel-1 SAR data (VV and VH polarization) proved to be the most critical predictor variables across all models. These findings hold practical significance for utilizing multi-source remote sensing data in STN mapping and precision fertilization in agricultural fields15.

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# Mapping Soil Particle Size Distribution: Fine Earth and Coarse Fragments Using Compositional Methods

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**ABSTRACT**

MapBiomas Soil is a collaborative initiative that produces annual soil information for Brazil through successive collections that incorporate new data and methodological innovations. Collection 3 introduces a compositional modelling strategy to represent soil particle-size fractions and coarse fragments consistently across the soil profile at the national scale.

Harmonized field soil observations from the SoilData repository (60,883 particle-size observations) were integrated with environmental covariates within a digital soil mapping framework implemented in Google Earth Engine at 30 m spatial resolution. Sand, silt, clay (fine earth), and coarse fragments (all particles larger than sand) were modelled jointly as components of the whole soil using additive log-ratio (alr) transformations, with clay as the References component. Modelling was performed on a mass basis, with fine-earth fractions rescaled to sum to 100% (sand + silt + clay) before compositional transformation. Gradient Boosted Model Trees (GBM) were fitted separately for successive 10 cm depth intervals from the surface to 100 cm.

Predicted fractions were back-transformed to the original compositional space to reconstruct particle-size distributions at each depth. Coarse-fragment mass fractions were converted to volumetric proportions using density estimates for fine earth and lithological materials. Depth intervals in which coarse fragments accounted for 100% of the soil volume were interpreted as the effective termination of the soil profile. Functional soil depth metrics were derived using two thresholds: dominant stoniness (50% coarse-fragment volume) and extreme stoniness (90%).

Results show that, while medium-textured soils dominate the surface layer (0–30 cm) across Brazil, clayey textures become predominant between 60 and 100 cm depth at the national scale. Sandy and coarse-textured soils are more frequent in savanna and semi-arid regions, whereas fine-textured soils dominate humid forested regions. Maps of coarse-fragment volume indicate that most of the Brazilian territory is characterized by low stoniness, but localized shallow and highly stony soils impose strong vertical constraints on soil depth and land-use suitability.

This modelling framework enables the consistent derivation of particle-size fractions, texture classes, and functional soil depth at large spatial extents and represents the main methodological innovation of MapBiomas Soil Collection 3, with potential applicability to other national-scale soil information systems.

Keywords: digital soil mapping, soil texture, Brazil, machine learning, pedometrics.

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# Distributional Validation of Digital Soil Maps using Aggregated Commercial Data

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**ABSTRACT**

Digital soil mapping (DSM) in extensive territories often relies on sparse geoReferencesd profiles, despite the existence of massive volumes of soil analyses in commercial laboratory databases. The utility of this commercial data is frequently limited by privacy restrictions and lack of coordinates, generally aggregated to the municipality level. This study proposes an alternative for utilizing such data by investigating a “distributional consistency check" as a complementary validation strategy for national-scale soil maps. We propose a methodological framework to assess whether 30m-resolution DSM predictions can be reliably evaluated against aggregated, non-geoReferencesd datasets. The investigation focuses on developing quantitative diagnostics that can function despite the uncertainty of sample support (unknown mix of point samples and field composites). We evaluate statistical resampling techniques to generate synthetic sample vectors from aggregated, binned frequency data from commercial laboratories, aiming to estimate population parameters while accounting for quantization uncertainty. We assess whether distributional comparisons (e.g., dispersion and shape alignment) remain valid when the physical support of the References data is unknown. We investigate theoretical bounds to distinguish between legitimate scaling effects (field averaging) and potential map errors (smoothing artifacts). We then test the sensitivity of histogram dissimilarity metrics to identify those most suitable for detecting systematic biases between the predicted map and the commercial "ground truth," regardless of the underlying sampling scheme. Among these, we introduce the Wasserstein metric (Earth Mover's Distance)—a measure that honors the topology of the histogram space and has been underexplored in pedometrics—as a useful diagnostic tool. This work aims to determine the operational viability of using non-spatial commercial data to quality-check digital soil maps. By rigorously testing these distributional diagnostics, we seek to establish a protocol that allows for the utilization of available commercial data to ensure map consistency with regional agronomic statistics.

**Keywords:** Commercial Soil Data, Distributional Validation, Bootstrap Resampling, Histogram Analysis, Brazil.

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# Modelling and mapping land susceptibility to degradation and desertification in Europe

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**ABSTRACT**

Land degradation and desertification emerge as increasingly serious environmental challenges, impacting extensive regions worldwide, including large areas of Europe. Achieving a comprehensive understanding of these complex degradation processes requires the application of multicriteria integrated approaches, such as the MEDALUS (*Mediterranean Desertification and Land Use*) framework, which has been widely applied in scientific studies to identify land areas sensitive to degradation and desertification across multiple spatial scales. This scientific work investigates land susceptibility to degradation and desertification at a continental scale by integrating, modelling and mapping various environmental factors responsible for land degradative conditions, which were derived from multiple geospatial datasets covering 40 European countries. More specifically, using a significantly improved MEDALUS framework, a total of 24 environmental variables and 7 environmental quality indices were integrated and processed as direct and indirect driving forces of environmental degradation. The refinement of the MEDALUS framework is justified by its methodological flexibility and the geographical diversity of Europe (with multiple environmental conditions influencing land degradation and desertification), and involved the integration of 11 new environmental parameters (in addition to 13 variables of the original MEDALUS scheme) and 3 supplementary quality indices (in addition to 4 standard indices) into a final geospatial product, called Land Degradation and Desertification Sensitivity Index. The cartographic results revealed a complex and heterogeneous spatial pattern of land susceptibility to degradation and desertification across Europe, with many hotspots of environmental degradation throughout the continent and with significant epicenters of desertification, particularly in the Mediterranean region. The geospatial (and statistical) findings provide a comprehensive assessment of pan-European lands exposed to varying levels of degradation and desertification, delivering useful insights for the European Union's and governmental policies addressing these environmental threats across the continent.

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# Soil Organic Carbon Spectral Modeling with MIR in Carbonate-Rich Soils Requires Temperature Ramping References Data for Reliable Training.

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**ABSTRACT**

We evaluated whether errors in predicting soil organic carbon (SOC) via Near Infrared (NIR) with models developed via acid digestion References values can be eliminated by using Mid Infrared (MIR) spectra. NIR and MIR spectral data were acquired on soil samples ($n$ = 403) collected from carbonate-rich Saskatchewan agricultural soils, and values for organic and inorganic carbon were measured with both acid digestion and temperature ramping methods. Soil spectra were processed with continuous wavelet transform then analyzed with cubist regression models using a 70:30 train-test split approach. Spectral feature selection, wavelet scales, models and hyperparameters were optimized on the training dataset using 5-fold cross-validation, while model validation was performed on the testing dataset. Temperature ramping data led to separation of spectral features selected for SOC and SIC model training, whereas acid digestion References data showed overlapping features at 9940, 8156, 7231, and 4199 $cm^{-1}$. The temperature ramping method resulted in higher model accuracy for SOC and SIC compared to the acid digestion method for both NIR and MIR. Applying spectral features selected from temperature ramping data to train models on acid digestion References values did not affect SOC and SIC model accuracy. This study concluded that model performance differences are driven more by the quality and consistency of the References data rather than the choice of spectroscopic wavelength or spectral feature selections.

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# Evaluating Portable Miniaturized NIR and Vis-NIR Technologies for Soil Spectroscopic Analysis

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**ABSTRACT**

Traditional soil testing is slow and costly. Visble-near infrared (Vis-NIR) spectroscopy offers a faster alternative for precision agriculture and soil health assessment. A compact Micro NIR sensor (NIRONE, 2000–2450 nm) was compared to a mobile Vis-NIR system (305-1700 nm) to predict pH, total organic carbon (TOC), phosphorus (P), potassium (K), magnesium ($Mg^{2+}$), and calcium ($Ca^{2+}$). spectra of prepared soils (n=145) were modeled with Partial Least Squares Regression (PLSR), Support Vector Machines (SVM), and Random Forest (RF) under 5-fold cross-validation and an independent test set. Many preprocessing pipelines (smoothing, derivatives, SNV, MSC, detrending, baseline correction) were optimized and used to enhance the predictive accuracy of the models. The micro-NIR often matched the Vis–NIR for several targets: pH (micro-NIR R = 0.84, RMSE = 0.24; Vis-NIR R = 0.74, RMSE = 0.27), TOC (0.83, 1.62 %; 0.86, 1.12 %), K (0.74, 6.42 mg/100 g; 0.77, 6.15 mg/100 g), and $Ca^{2+}$ (0.87, 463.9; 0.88, 457.7 mg/100 g). The Vis-NIR was stronger for $Mg^{2+}$ (0.79, 5.9 mg/100 g vs 0.59, 9.29 mg/100 g). Both instruments showed only modest predictive accuracy for P (Vis–NIR 0.56, 7.01 mg/100 g; micro-NIR 0.5, 9.11 mg/100 g). Across properties, preprocessing optimization and algorithm choice were the main drivers of accuracy; no single pipeline dominated. The micro-NIR sensor shows strong potential for soil property prediction and is suitable for routine laboratory and field measurements due to its compact size, low cost, and competitive predictive accuracy.

**Acknowledgments**

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# Intelligent Soil Monitoring

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**ABSTRACT**

The advancement of soil remote sensing toward intelligent monitoring and information-based management requires the integration of spectral theory, multi-source data fusion, and artificial intelligence. This presentation summarizes a five-part research framework that progressively builds from physical spectral mechanisms to large-scale, intelligent soil information systems.

Section One: Fractional-order Derivative (FOD)

Fractional-order derivative introduces a continuous mathematical formulation to enhance soil spectral information processing. By adjusting derivative order within a non-integer domain, FOD effectively amplifies subtle spectral features while maintaining signal integrity. This method advances traditional preprocessing techniques by balancing spectral resolution and stability, providing a new theoretical foundation for intelligent spectral analysis across soil and environmental sensing applications.

Section Two: Multi-sensor Spectral Fusion

The integration of visible–near infrared (VIS–NIR) and mid-infrared (MIR) spectral data represents a key step toward multi-source information synergy. Through algorithms such as continuous wavelet transform and optimal band combination, complementary features from multiple spectral domains are jointly utilized to enhance prediction accuracy and efficiency. This multi-sensor fusion demonstrates the potential of cross-domain spectral integration for soil property monitoring and data-driven environmental assessment.

Section Three: Large Soil Spectral Library

Global and regional soil spectral libraries serve as essential data infrastructures for intelligent soil monitoring. Leveraging big-data analytics, fractional-order transformations, and deep learning models such as convolutional neural networks (CNN), large-scale libraries enable robust and transferable models despite data heterogeneity. These databases function as both knowledge repositories and algorithm training grounds, laying the foundation for universal soil spectral intelligence systems.

Section Four: Airborne Hyperspectral Observation

Airborne hyperspectral imaging provides fine spatial and spectral detail for soil mapping at field to landscape scales. As an intermediate observation level between laboratory and satellite sensing, airborne platforms enable the validation and refinement of predictive models under real-world environmental conditions. Their integration into soil monitoring workflows enhances both spatial continuity and spectral interpretability, supporting precision agriculture and environmental diagnostics.

Section Five: Bridging Laboratory Spectra and Satellite Imagery

To achieve large-area and cost-effective soil monitoring, an integrative framework was developed to link laboratory VNIR–SWIR spectra with multispectral satellite data. By simulating hyperspectral features from Landsat-8 imagery and applying fractional-order preprocessing, this approach reduces the scale and spectral gaps between in-situ measurements and satellite observations. The resulting system enables consistent, scalable, and intelligent SOC prediction and mapping under natural conditions.

Collectively, these five research directions outline a comprehensive pathway toward intelligent soil remote sensing, characterized by adaptive spectral modeling, data-driven fusion, and multi-platform integration. This framework not only enhances the monitoring of soil carbon but also establishes a methodological foundation for digital, automated, and knowledge-based soil information systems in support of sustainable land and ecosystem management.

# Evaluating Portable X-Ray Fluorescence (pXRF) for Soil Fertility Assessment: Influence of Moisture and Soil Properties

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## ABSTRACT

Rapid and scalable soil health assessment is essential for precision agriculture, yet routine wet-chemistry analyses remain slow, and costly for large-area monitoring. Portable X-ray fluorescence (pXRF) spectroscopy offers a promising proximal-sensing solution for rapid multi-element detection, but its performance is often constrained by soil moisture, matrix effects, and the weak relationship between total and plant-available nutrient pools. This study evaluated 113 soils collected from 0-120 cm depth across eastern Washington to (i) quantify how soil moisture influences pXRF elemental detectability, (ii) develop prediction models for soil pH and available nutrients, and (iii) assess the potential of pXRF-based predictions for regional soil health mapping. Soils were analyzed under four moisture states: dry (DS), field-moist (FM), saturated paste (SP), and after removal of excess water (AREW) to reflect realistic field and laboratory scenarios. Moisture substantially affected pXRF signals, with mobile elements showing greater attenuation than immobile mineral-bound elements. Despite this, pXRF exhibited strong predictive capacity for macronutrients such as K, Ca, and Mg ($R^2$ up to 0.8 in DS and SP). Prediction accuracy improved markedly when soil pH and organic matter (OM) were incorporated into regression models, increasing $R^2$ values by 1.1 - 6.1-fold compared to pXRF-only models. Micronutrient predictions (Cu, Zn) were weaker, driven by low concentrations and greater geochemical variability. Among moisture conditions, SP consistently produced the most stable models, likely due to improved particle homogeneity and surface smoothness that reduce density-related X-ray scattering. Cross-validation confirmed strong generalization for macronutrients but lower stability for Cu and Zn. Spatial mapping using pXRF derived predictions reproduced regional gradients of acidity and nutrient status, demonstrating strong utility for reconnaissance level soil health surveillance. However, agronomic category comparisons revealed variable agreement with laboratory data: Ca and Mg classifications were highly stable (<3% mismatch), whereas pH, P, and Cu showed higher misclassification near critical management thresholds. Thus, pXRF based predictions can guide regional monitoring and sampling prioritization, however laboratory confirmation remains necessary for fertilizer recommendations. Overall, combining pXRF with key soil properties under controlled moisture conditions enhances the speed, resolution, and practicality of soil fertility monitoring. This work demonstrates the growing potential of proximal sensing technologies to serve as foundational tools in future soil fertility assessment systems.

# Low-cost portable near infrared spectroscopy for in-situ and laboratory prediction of soil organic carbon in Ferrosols

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**ABSTRACT**

Soil organic carbon (SOC) is critical to maintaining soil health and ecosystem functioning. Reliable quantification of SOC is therefore essential for evaluating soil fertility and guiding carbon management strategies. near-infrared spectroscopy (NIRS) provides a rapid, non-destructive, and cost-efficient approach for SOC estimation; however, conventional commonly used spectrometers remain prohibitively expensive for widespread use. This study evaluated the potential of the low-cost portable NeoSpectra spectrometer for SOC prediction using soils from typical Ferralsols collected in Jiangxi Province, China. The spectral data were converted to absorbance and processed using the Savitzky–Golay first-derivative smoothing before model calibration. Predictive models included Cubist, random forest (RF), partial least squares regression (PLSR), memory-based learning (MBL), a simple ensemble model, and a spectral-guided ensemble approach. For in-situ condition, the ensemble and spectral-guided ensemble models performed best, with coefficient of determination (R2) of 0.72 and 0.70, and root mean square error (RMSE) of 5.95 g kg-1 and 6.16 g kg-1, respectively. The RF model showed slightly lower yet acceptable performance (R2 = 0.62, RMSE = 6.90 g kg-1). For laboratory condition, the two ensemble strategies again outperformed the other models (R2 = 0.85 and 0.85; RMSE = 4.15 and 4.07 g kg-1), while the RF model remained acceptable ($R^2$ = 0.77, RMSE = 5.10 g kg-1). These findings demonstrate that the NeoSpectra spectrometer, when combined with appropriate preprocessing and ensemble modeling, can provide reliable SOC estimates, representing a viable and lower-cost alternative for routine soil monitoring and regional carbon assessments.

**Acknowledgments**

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# Sequential indirect modeling of soil properties from spectral data with small sample set

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**ABSTRACT**

Modern agricultural monitoring demand precise and timely information of soil properties. In recent years, soil spectroscopy has become widespread method as an effective alternative to traditional laboratory analysis of soil samples [1]. However, existing approaches encounter a range of methodological constraints, among which is a dependence of model accuracy on the sampling size. Spectral prediction of soil properties mainly is based on large datasets (n > 100), which often is not easy to collect. Practical survey are often restricted to 20-50 samples per field, primarily due to economic and time constrains. When soil properties are highly correlated with each other, predicting each property individually directly from the spectra can be optimized. This can be done by indirect prediction [2].

The objective of our study was to develop a sequential indirect modeling (SIM) method for predicting soil properties from spectral reflectance data with small sample datasets (n = 30). We focus on analysis of the relationship between soil properties (SOC, available P, total N, pH, and main exchangeable cations) and soil samples spectra, and perform SIM method among the most highly correlated properties. It allows for the indirect prediction of parameters that are difficult to model directly (for example, pH or available P) through those that are more easily predicted (for example, SOC content). The physicochemical validity of these relationships (for example, the correlation between SOC content and total N) provides additional reliability of predictions.

SIM approach for several soil properties was successfully tested on a number of plots. The most effective method proved to be regression techniques such as PLSR, PCR, RF, SVR. These methods enable efficient use of the available data, minimize the negative effects associated with small sampling sizes, reduce the risk of overfitting, and provide reliable predictions. The outcomes of this analysis were employed to enhance the accuracy of agrochemical soil mapping under constrained resources for sampling and analysis.

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# Sensor-based monitoring of Soil EC responses to nitrogen and potassium fertilization under laboratory and field conditions

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## ABSTRACT

Appropriate nutrient management is essential for improving nutrient use efficiency and preventing environmental pollution caused by excessive fertilizer application. Therefore, continuous monitoring of soil nutrient levels during crop growth is required. However, there are no available sensors for real-time measurement of soil nutrient contents. Since electrical conductivity (EC) reflects ionic concentrations in soil solutions, this study evaluated the applicability of EC sensors for real-time prediction of available nutrient levels in soil. The objective of this study was to assess EC sensor responses to nitrogen and potassium fertilization and to evaluate its applicability under field conditions. In the laboratory, nitrogen and potassium were sequentially applied to achieve cumulative application rates of 0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, and 3 times of the standard fertilization amount. The observed EC variations were analyzed to quantify the relationship between cumulative fertilizer input and sensor response. The increase in sensor-based EC responded linearly to fertilizer input between 0.25 and 1.25 times the standard fertilization rate, but at higher application levels, the relationship was better explained by a nonlinear saturation model. The sensor-based EC values showed a strong correlation with soil ammonium nitrogen ($NH_4^+$-N) released by urea hydrolysis, indicating that EC sensors effectively reflected the applied fertilizer in soil. In the open-field pepper soil, the increases in sensor-based EC following nitrogen and potassium fertigation were well predicted by the linear and nonlinear saturation models established through laboratory-based fertilizer monitoring. This indicated that the relationships established under laboratory conditions were also applicable under field conditions. Real-time monitoring of soil nutrients using EC sensors would be beneficial for nutrient management in open-field cultivation.

# Coastal Soil Salinity Inversion Using Resource Satellite Data and Explainable Machine Learning: A Case Study of Southern Laizhou Bay

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**ABSTRACT**

Soil salinization in coastal regions is a significant manifestation of global coastal land degradation, posing significant threats to agricultural sustainability and the stability of ecosystems.. In China, coastal areas are particularly affected by extensive salinization, making this issue increasingly urgent. Recent factors such as sea-level rise, seawater intrusion, and improper irrigation practices have further exacerbated coastal soil salinity. This study aims to quantitatively estimate soil salinity levels in the southern Laizhou Bay area using interpretable machine learning and feature selection strategies, with the goal of determining the extent and proportion of soil salinization.. The southern shore of Laizhou Bay in Shandong Province was selected as the study area. The research utilized four raw bands (blue, green, red, and near-infrared) from ZY1-02D VNIC, along with derived data: 9 vegetation indices, 13 salinity indices, three principal component datasets, and eight texture feature datasets. These were integrated with 66 measured soil salinity data points (ranging from 0.4 to 33 g/kg) to develop an inversion model for soil salinization. Correlations between 37 feature variables and soil salinity were first analyzed, with significant correlations at the 0.01 level retained for further examination.. Four feature selection methods: Grey Relational Analysis (GRA), Variable Importance in Projection (VIP), Gradient Boosting Machine (GBM), and Recursive Feature Elimination (RFE) were applied. Five machine learning models: Backpropagation Neural Networks (BPNN), Random Forest (RF), Classificatory Boosting Trees (CatBoost), Adaptive Boosting (AdaBoost), and Extreme Gradient Boosting (XGBoost) were tested. The optimal model was selected using grid search combined with five-fold cross-validation. The SHAP method was used to analyze the influence of input variables on model performance, resulting in an inversion map for the study area. The findings indicate that the GBM-BPNN model achieved the best performance for soil salinity inversion ($R^2$ = 0.72, RMSE = 4.24 g/kg, RPD = 1.94). Among the five feature categories, vegetation indices were found to play the most significant role, with four of the seven GBM-selected variables being vegetation indices ("GDVI", "GRVI", "GARI", "EVI"). SHAP analysis revealed that GRVI were the most influential. The results show that moderate and mild salinization dominate the Laizhou Bay area, comprising 56.4% of the total area. Salinity increases from south to north, consistent with results from back-distance weighted interpolation of measured samples. This study demonstrates that the proposed methodology offers superior accuracy compared to traditional geostatistical approaches and highlights the importance of feature selection when sample sizes are limited. Additionally, the study elucidates how features influence model performance, providing a scientific basis for coastal ecological management.

**Keywords:** soil salinity; explainable machine learning; ZY1-02D; SHAP; Laizhou Bay

# Deep Learning-Based Similarity Framework for Rapid Soil Organic Matter Assessment from Smartphone Imagery

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**ABSTRACT**

Rapid and accurate organic matter (SOM) determination is essential for sustainable agricultural management, but conventional laboratory analyses are expensive and time-intensive. Although smartphone-based soil imaging presents a viable alternative, existing methods suffer from limited accuracy and poor cross-condition generalization. We present a novel deep metric learning framework that transforms SOM prediction from a regression problem into a similarity-based learning task using smartphone-captured soil images. Our approach employs a Triplet Loss neural network architecture to map soil images into an embedding space where geometric distances reflect SOM content differences. The framework integrates automated image quality evaluation through the Blind/Referencesless Image Spatial Quality Evaluator (BRISQUE) combined with super-resolution enhancement to optimize input data quality. Testing with 500 soil samples from Southern Ontario revealed that our similarity-based framework (validation RMSE = 0.17) substantially outperformed conventional regression approaches (validation RMSE = 0.51 for Random Forest). The model exhibited robust performance across varying soil textures (RMSE variation <0.05 among texture classes) and diverse environmental conditions (temperature 20-30°C, humidity 45-75% RH). With a processing time of only 2.3 seconds per sample, the framework is well-suited for real-time field deployment. This similarity-based paradigm overcomes key limitations in digital soil sensing by enabling fast, accurate, and user-friendly SOM quantification, thereby advancing precision agriculture soil monitoring capabilities. Our results highlight the transformative potential of metric learning approaches for digital soil analysis and their contribution to sustainable farming practices.

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# Preprocessing and Optimizing Sensitive Wavelength Enable End-to-End Estimation of Soil Heavy Metals using Hyperspectral Remote Sensing

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**ABSTRACT**

Soil heavy metal contamination can lead to long-term environmental risks in mining areas. Hyperspectral remote sensing combined with machine learning models is a promising approach for monitoring soil heavy metal concentrations. However, the high dimensionality of soil spectra makes it difficult to directly use spectral data for accurate prediction, often leading to model overfitting. Therefore, key challenges for extracting spectral features and improving the accuracy and transferability of predictive models remain. This study aims to overcome these limitations by proposing an end-to-end hyperspectral remote sensing workflow to enhance model cross-regional applicability. In this study, 647 surface soil samples (0-20 cm) were collected from an abandoned tailing area in western Inner Mongolia. Soil spectral reflectance was measured using a PSR+ spectrometer, and soil heavy metal concentrations were determined using ICP-MS. To improve data quality, 11 preprocessing methods were applied, forming 180 combinations through baseline correction, scatter correction, smoothing, and scaling. These combinations were evaluated for their correlation and predictive performance, with the best combinations selected. Furthermore, 16 wavelength selection methods were tested, which were classified into filter, wrapper, and embedded approaches, focusing on Competitive Adaptive Reweighted Sampling (CARS), Variable Iterative Space Shrinkage (VISSA), and Successive Projections Algorithm (SPA). During the feature construction phase, Optimized Spectral Indices (Opt-TBIs) and Continuous Wavelet Transform (CWT) were used to improve the expression for inter-band information. Finally, the optimal wavelengths were combined with Decision Tree (DT), Random Forest (RF), and Gradient Boosting Decision Tree (GBDT) models to predict soil heavy metal concentrations. The results showed that the best-performing bands were obtained through pairwise combinations of preprocessing, with First Derivative (1FD) and Multivariate Scatter Correction (MSC) that was the most robust performance across all heavy metals. Regarding wavelength selection, the wrapper method exhibited the best prediction performance, with effective wavelengths concentrated in the 496–750 nm and 1829–2400 nm ranges. CARS and VISSA were more effective in capturing copper and chromium features, while SPA in predicting zinc and lead showed the best performance. Using Opt-TBIs to enhance inter-band correlation, combined with the GBDT model, demonstrates excellent predictive accuracy and stability, with an independent validation $R^2$ of approximately 0.87. In conclusion, the end-to-end hyperspectral remote sensing workflow enhances the accuracy and transferability of predictions for soil heavy metal concentrations, providing an innovative solution for monitoring soil contamination in mining areas.

**Keywords:** Gradient boosting decision tree; Optimized spectral indices; Sensitive wavelength selection; Soil heavy metals

# Multi-Element Synergy-Driven Transfer Learning Model for Enhancing the Generality of Soil Heavy Metal Concentration Estimating

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**ABSTRACT**

Soil heavy metal contamination poses a long-term threat to agricultural sustainability and ecological security. Remote sensing technology offers a non-invasive, large-scale method for monitoring soil heavy metal concentrations, providing an effective alternative to traditional soil analysis. However, monitoring models are often influenced by variations in soil active components (such as organic matter and iron) across regions, which can reduces model accuracy and generalization ability. To address this, this study proposed a multi-element synergistic transfer learning model (Tr-MORF), which leverages the inherent absorption characteristics and antagonistic effects between metals and soil active components to solve domain adaptation problems in cross-regional predictions. In this study, 488 surface soil samples (0-20 cm) were collected from two tailing areas in western and northern Inner Mongolia. Soil spectral reflectance was measured using a PSR+ spectrometer, and heavy metal concentrations and active soil components were analyzed through laboratory wet chemical methods. To enhance spectral reflectance, a Fractional Order Derivative (FOD) method was used to highlight subtle spectral features. The MORF model was then employed to jointly predict concentrations of Zn, Cr, As, Cd, Pb, and Cu. To further improve cross-regional prediction accuracy, several transfer strategies (Recalibrated, Parameter-based, TCA, KMM, and TrAdaBoostR2) were integrated into a multi-output framework to assess their adaptability in estimating soil heavy metal concentrations. The results showed that the 1.2-order FOD method significantly improved the capture of subtle spectral features and enhanced spectral expression. The key soil heavy metal bands selected by the FOD-enhanced MORF model were found in regions associated with active soil components, indicating a synergistic effect between metals and active components. Joint modeling effectively integrated this information reduced negative impacts and enhanced the model's generalization ability. The combination of transfer learning and the MORF model significantly improved cross-regional transferability, with nRMSE decreasing by 6.35% to 11.24% and $R^2$, which was increased by 7.05% to 16.04%. Cu, Pb, and Zn exhibited the highest transferability, followed by Cd and As. Notably, the Tr-MORF model demonstrated high prediction accuracy and consistency when validated with publicly available soil data, demonstrating its applicability across different regions and scales. In conclusion, the Tr-MORF transfer learning model significantly improves adaptability and transferability across regions, providing an innovative solution for precise soil pollution monitoring.

**Keywords:** fractional-order differentiation; multi-output modeling; soil heavy metals; transfer learning

# A transferable spatiotemporal deep learning framework integrating soil moisture dynamics for high-resolution cropland Soil Organic Matter Mapping Across Regions

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**ABSTRACT**

Soil organic matter (SOM) is a critical indicator of soil health and agricultural sustainability, yet achieving high-resolution mapping at large scales remains challenging due to the complex interplay of environmental drivers, particularly soil moisture dynamics. This study introduces a novel spatiotemporal deep learning framework, ExP-C, that incorporates reconstructed soil moisture dynamic feedback sequences (SMDFS) to enhance SOM prediction accuracy. Focusing on two major black soil regions—Northeast China (1.24 million km²) and the U.S. Mississippi River Basin (1.35 million km²)—we compiled 2,616 topsoil (0-20 cm) samples from field surveys (2014-2024) and the WoSIS database, integrated with Landsat-8 OLI bare-soil composites, SRTM-derived topographic variables, and ERA5 meteorological data. SMDFS were generated via percentile reconstruction of multi-temporal moisture indices (MNDWI, NDWI, NDMI) to capture dynamic feedbacks between SOM levels and moisture retention. The ExP-C model fuses expert convolutional networks for spatial contextual extraction from static covariates, pyramid 1D convolutions for multi-scale SMDFS pattern mining, and contrastive learning to bolster feature representations, with transfer learning (pre-training on Chinese data, fine-tuning on U.S. data) enabling cross-regional adaptation. Ten-fold cross-validation yielded superior performance for ExP-C compared to random forest and CNN-LSTM baselines: $R^2 = 0.712$ (RMSE = 6.221 g/kg) in China and $R^2 = 0.554$ (RMSE = 7.693 g/kg) in the U.S. when integrating SMDFS with spatial features, with SMDFS alone boosting $R^2$ by 11-14% on static inputs. Gradient-based attribution confirmed SMDFS and elevation as dominant contributors, underscoring their mechanistic role in SOM variability. Transfer learning further improved U.S. predictions to $R^2 = 0.572$ (RMSE = 7.597 g/kg) using a partial freeze strategy on spatial branches. High-resolution (30 m) SOM maps revealed north-south gradients in both regions, with mean contents of 32.0 g/kg (China) and 36.8 g/kg (U.S.), and low uncertainty (means of 4.03 and 4.79 g/kg, respectively). This framework advances SOM mapping by explicitly modeling moistureSOM feedbacks, offering a robust, transferable approach for monitoring carbon dynamics in global croplands and informing sustainable management.

**Keywords:** Soil organic matter (SOM), Soil moisture dynamics, Transfer learning, Deep learning (DL)

# Regional bare soil mapping method integrating multi-source remote sensing data in cloudy environments

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**ABSTRACT**

Persistent cloud cover presents a fundamental constraint for continuous monitoring of bare soil dynamics through optical remote sensing in perennially cloudy regions. To address this limitation, this study proposes an integrated computational framework that synergistically combines multi-source remote sensing datasets, including Sentinel-1 Synthetic Aperture Radar (SAR) imagery, Harmonized Landsat Sentinel-2 (HLS) surface reflectance composites, and high-resolution topographic derivatives. The methodology advances current approaches by strategically incorporating microwave-based feature descriptors, thereby constructing a multidimensional discriminative feature space through the fusion of optical spectral indices, SAR-derived metrics, and geomorphological parameters. This integrative feature engineering significantly enhances the separability between bare soil and spectrally similar land cover classes. The approach provides a technically sound foundation for precision agriculture planning, spatially explicit soil erosion modeling, and systematic land degradation assessment, establishing an operational paradigm for dynamic soil exposure monitoring in cloud-affected environments.

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# Accuracy improvement of spatial prediction for soil organic matter using receptive field fusion module in hilly areas

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**ABSTRACT**

Accurate prediction of soil organic matter (SOM) is essential for maintaining soil security and supporting agricultural production. In the field of SOM mapping, convolutional neural networks (CNNs) mainly focus on local receptive fields for feature extraction, lacking attention to global receptive fields, especially in complex landscapes such as hilly regions, where SOM has high spatial heterogeneity and accuracy improvement is difficulty in prediction. This study proposes a highly flexible Receptive Field Fusion Module (RFFM) that can be seamlessly integrated into any CNN architecture. RFFM includes a Global Receptive Field Block (GRFB) and a Local Receptive Field Block (LRFB). GRFB aims to capture global dependencies on feature dimensions, while LRFB focuses on local feature associations. And based on RFFM, a new model for SOM prediction (RFFM-SOMPNet) was proposed, which integrated these two different feature scales to improve the accuracy of SOM prediction. The experiment conducted in the hilly area, Longshan County, Hunan Province, China, shows that RFFM-SOMPNet has better predictive performance, with an $R^2$ improvement of 9.67% compared to the benchmark model. In addition, differences in SOM spatial patterns between concentrated and scattered distribution areas of cropland were discovered, and the reasons for these differences were explored through uncertainty analysis and variable contribution analysis. The results indicate that RFFM can effectively integrate global and local receptive fields, improve SOM prediction accuracy, and provide reliable data support for ensuring soil safety and supporting sustainable agricultural production.

**Keywords:** Cropland, Deep learning, Receptive field, Convolutional neural network, Soil organic matter

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# Towards Sustainable Land Use: Soil Health Assessment at a National Scale using Spectral Information

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**ABSTRACT**

Agriculture covers 53% of the total land area in the Czech Republic, with the majority of agricultural properties being leased. This raises concerns about soil conservation, as short-term gains may take precedence over long-term soil health. In practice, farmers primarily enhance productivity through fertilization, often without considering key factors such as carbon (C) content, biological activity, and soil compaction. The aim of this study was to develop a soil health index map for the Czech Republic using remote sensing and machine learning techniques. A bare topsoil proxy, derived from satellite data, was combined with spatialized soil properties from four different databases. The generated maps were used to assess three critical soil functions: nutrient storage and cycling (f1), carbon storage (f2), and support for plant growth (f3). These functions were then integrated to generate the soil health index map for the country. The predictive models for C and cation exchange capacity (CEC) outperformed global averages, likely due to the incorporation of bare soil reflectance and a robust dataset. In contrast, the prediction of nutrients such as nitrogen (N), phosphorus (P), and potassium (K) showed lower performance, reflecting their high spatial variability due to land management practices. The soil health index (SHI), calculated from the standardized property maps, ranged from 0.26 to 0.70, with most areas exhibiting intermediate values. Forests and agricultural lands showed similar SHI distributions, indicating limited soil resilience across land uses. This approach effectively captured spatial variability in soil properties and facilitated the assessment of soil functions related to erosion, organic matter depletion, and compaction. These findings offer a comprehensive understanding of soil conditions and provide valuable insights for sustainable land-use planning.

**Keywords:** Agricultural lands, Soil health index, Remote sensing, Machine learning, Sustainable land use

**Acknowledgments**

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# Metagenomic tools for soil health–oriented microbial monitoring in agricultural systems in Mexico

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**ABSTRACT**

Wildfires disrupt soil structure and alter microbial diversity, reducing ecosystem resilience and delaying natural recovery. Restoring native soil microbiomes may enhance plant fitness and promote the degradation of toxic combustion by-products such as PAHs and PyOM. To identify key bacterial taxa with potential for microbiome- based remediation, we investigated wildfire-driven shifts in soil bacterial communities across a pine–oak forest in Mexico. Sixteen soil samples were collected from burned and unburned areas representing three post-fire recovery stages. Bacterial communities were characterized using 16S rRNA Illumina MiSeq sequencing and QIIME1, complemented by physicochemical analyses and culture-based isolation followed by MALDI-TOF identification.

Time since wildfire emerged as a major determinant of community composition, with significant variation along pH and elevation gradients. Burned and unburned soils differed in the relative abundance of Actinobacteria and Acidobacteria and showed enrichment of thermotolerant and pollutant-degrading taxa. Although 50% of species were shared between conditions, co-occurrence network analyses revealed higher connectivity in unburned soils, suggesting greater community stability. Pyrophilous genera such as *Massilia*, *Arthrobacter*, and *Blastococcus* were detected, with *Arthrobacter* and *Blastococcus* forming part of the core microbiome and highly connected network modules.

Culture-based analyses yielded 275 bacterial isolates, of which 126 were identified and assigned to 50 species.

Burned soils exhibited higher cultivable diversity than unburned soils. Dominant species included *Achromobacter xylosoxidans*, members of the *Enterobacter cloacae* complex, and *Bacillus cereus*. Notably, several isolated taxa were not detected by amplicon sequencing, highlighting the complementarity of cultivation-dependent and - independent approaches.

Overall, these results emphasize the value of integrating sequencing, network analysis, and culturable microbiome approaches to identify key bacterial taxa for microbiome-based restoration strategies in fire-prone ecosystems.

**Acknowledgments**

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# Improving in-situ spectral estimation of wetland soil organic carbon by integrating multiple optimization strategies

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**ABSTRACT**

Carbon in wetlands is a critical component of the terrestrial carbon pool in the global carbon cycle. Accurate quantification of wetland soil organic carbon (SOC) is essential for sustainable wetland management and climate change mitigation. However, this effort is often hampered by the inaccessibility of wetlands and high economic and labor costs associated with data acquisition. The advent of visible and near–infrared (Vis-NIR) spectroscopy offers a time- and cost-effective method for monitoring SOC content. Considerable efforts have been directed toward estimating wetland SOC using Vis-NIR spectroscopy. However, great differences were reported for the performance of different predictive strategies, which pose confusion in the choice of methods when using Vis-NIR spectroscopy to estimate SOC. Therefore, this study aims to improve the in-situ spectral estimation accuracy of wetland SOC by testing and evaluating 240 optimization strategies which integrate different pre-treatment technologies, moisture removal algorithms, spectral feature selection methods. Our findings indicate that the optimal strategy involved the combination of first-order derivative (1stD), external parameter orthogonalization (EPO), modified greedy feature selection (MFGS), and one-dimensional convolutional neural network (1D-CNN), yielding $R^2$, RPD, RMSE values of 0.94, 4.15, and 1.09 g/kg, respectively. For pre-treatment technologies, 1stD outperformed Savitzky-Golay (SG) and log(1/reflectance) (Log(1/R)). EPO emerged as the optimal moisture removal algorithm, effectively reducing the interference of moisture and other environmental factors. Among spectral feature selection methods, the competitive adaptive reweighting algorithm (CARS) outperformed Boruta, MFGS, and interval random frog (IRF). In terms of prediction models, the 1D-CNN model significantly outperformed partial least squares regression (PLSR) and random forest (RF), with markedly higher accuracy (averaged $R^2$ = 0.83, RPD = 2.74, RMSE = 1.76 g/kg). Findings from this research could guide future studies in selecting the optimization strategies to more accurately estimate wetland SOC via Vis-NIR spectroscopy.

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# Spatio-temporal fusion–based analysis of soil salinization dynamics in the Ningxia–Inner Mongolia Yellow River Irrigation District (2000–2025)

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**ABSTRACT**

Soil salinization poses a severe challenge to global agricultural productivity, ecosystem resilience, and the sustainable use of regional resources. Under the combined impacts of climate change and unsustainable land-use practices, both primary and secondary salinization processes driven by natural and anthropogenic factors have continued to intensify, seriously threatening food security and soil health in arid regions. Existing studies largely rely on single-source remote sensing data and short-term inversion models, which are insufficient to support long-term dynamic analyses of soil salinity. To address this limitation, this study developed a deep learning–based multi-source remote sensing data fusion framework that synergistically integrates MODIS and Landsat 5/7/8/9 imagery to generate surface reflectance datasets with high spatio-temporal consistency. Combined with field-measured data, soil salinity inversion models based on Support Vector Machines (SVM), Random Forests (RF), and Convolutional Neural Networks (CNN) were constructed to systematically map soil salinity dynamics and analyze evolutionary trends in the Ningxia–Inner Mongolia Yellow River Irrigation District from 2000 to 2025.The results indicate that soil salinity in the study area ranges from 0.39 to 17.38 $g \cdot kg^{-1}$, exhibiting pronounced spatial heterogeneity. The deep learning–fused imagery outperformed the original datasets in both spectral fidelity and spatio-temporal continuity, effectively balancing temporal consistency required for long-term monitoring with the preservation of spatial detail. Among the models, the CNN achieved significantly higher inversion accuracy than the RF and SVM models. The mapping results further reveal a continuous expansion of non-saline soils, a marked reduction in severely salinized soils and saline soils, and stage-wise fluctuations in the areas of slightly and moderately salinized soils, reflecting the notable effectiveness of salinity control measures in the region. Overall, soil salinity in the Ningxia–Inner Mongolia Yellow River Irrigation District has shown a declining trend over the past two decades, although significant local fluctuations persist. This study demonstrates the advantages of deep learning–based fusion frameworks for long-term dynamic monitoring of soil salinity and provides methodological support for precision management of saline–alkali lands and the development of soil salinity prediction models at the regional scale.

**Keywords:** Soil degradation; multi-source remote sensing imagery; deep learning; spatio-temporal dynamics

# SWRCI: A Novel Remote Sensing Index for Soil Water Retention Capacity

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**ABSTRACT**

Soil water retention capacity (SWRC) is a key indicator affecting crop growth and ecosystem water dynamics. To address the inefficiency of traditional field work, this study selected Youyi and Heshan farm in Heilongjiang Province as the study area, and constructed the soil water retention capacity index (SWRCI) based on the time series sensor soil moisture and the 2020-2025 Sentinel-2A Normalized Difference Water Index (NDWI). Second, time series NDWI from snow cover to bare soil was selected, and the mathematical model was used to fit the time series sensor soil moisture and NDWI; Then, the characteristic parameters of the time series were extracted to construct the SWRCI, and validated by the measured sensor soil moisture and measured field capacity (FC). Finally, we analyzed the spatial patterns of the SWRC. Results showed that the time series NDWI and sensor soil moisture show significant consistent with the soil water retention curve (SWRTC) trends, reflecting different soil degradation types. And they were effectively described by an exponential decay fitting model (EDFM) ($R^2$=0.84–0.99). The SWRCI could effectively indicate the degree of soil degradation and was significantly correlated with soil organic matter ($p<0.001$, R=0.78–0.84), texture (sand: $p<0.001$, R=−0.8–−0.75, silt and clay: $p<0.001$, R=0.71–0.79), and crop yield ($p<0.001$, R=0.78–0.79). Furthermore, the performances of SWRCI in quantifying soil degradation have been validated across the two study areas. The study offers new tools for precision water management and degraded-soil restoration, with strong theoretical and practical value.

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# The Accurate Estimation of Soil Available Nutrients Achieved by Feature Selection Coupled with Preprocessing Based on MIR and pXRF Fusion

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**ABSTRACT**

Rapid assessment of soil available nutrients is essential for precision agriculture. The proximal sensors offer promising technologies for soil available nutrients estimation. However, the prediction accuracy of AP and AK remains challenging for both single and multi-sensor fusion approaches due to low concentrations and weak spectral features. To further improve fusion model accuracy, this study, integrating mid-infrared (MIR) and portable X-ray fluorescence (pXRF) spectroscopy, systematically evaluated the impact of various preprocessing methods and band-selection algorithms on soil nutrient prediction models in Hebei Province, China. Four types of models were compared: (1) single sensor; (2) direct concatenation (DC); (3) feature-level fusion (FU) using sCARS or a novel Adaptive Importance-driven Feature Refinement with Correlation (AIFC) algorithm; and (4) decision-level fusion employing Granger-Ramanathan Averaging (GRA) and Bayesian Model Averaging (BMA). Partial least squares regression (PLSR) and Cubist were employed.

Results showed that sensor fusion significantly improved prediction accuracy. The feature-level fusion Cubist model for AP achieved $R^2_V = 0.83$, outperforming single sensors ($0.68 \leq R^2_V \leq 0.73$). Decision-level fusion models for AK elevated predictions from $R^2_V < 0.65$ to 0.68. Critically, SNV preprocessing proved essential for PLSR fusion, ensuring balanced sensor contributions (11.05–88.95%), while other preprocessors biased predictions toward pXRF. The AIFC algorithm enhanced AP prediction to $R^2_V = 0.83$ using only 8.40% and 0.93% of MIR and pXRF bands, outperforming single sensor ($R^2_V = 0.73$) and DC models ($R^2_V = 0.78$). For SOM and TN, MIR alone achieved $R^2_V = 0.89$, equal to fusion models.

In summary, this study highlighted the necessity of SNV in constructing feature-level fusion PLSR models and demonstrated that sensor fusion of MIR and pXRF could be an alternative approach for the accurate prediction of AP and AK.

**Acknowledgments**

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# A Dataset-Based Statistical Comparison and Fusion of Gamma-Ray and Visible-Near-Infrared Sensing Technologies for Soil Texture Prediction

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**ABSTRACT**

Soil texture plays a crucial role in environmental and agricultural applications. Traditional methods for soil texture determination are labor-intensive, costly, and time-consuming. This study compares the performance of proximal gamma-ray and vis-near-infrared (vis-NIR) sensors and the potential of fusing of these two technologies for soil texture measurement. A total of 197 soil samples were collected from 11 agricultural fields in Belgium and France and analyzed using a gamma-ray sensor (0-3 MeV), a fiber-optic vis-NIR sensor (305-1700 nm), and a micro-NIR sensor (2000-2450 nm). Gamma-ray data were processed using both the region of interest (ROI) and gamma-ray full spectrum (GFS) methods. The dataset was randomly divided into a training set (75 %) and a test set (25 %). Partial least squares regression (PLSR), support vector regression (SVR), and random forest (RF), were used to develop predictive models for clay, silt, and sand contents. Early-level, feature-level, and decision-level fusion methods were applied for fusing the two sensing technologies. The results indicate that micro-NIR demonstrated superior performance in clay prediction, while gamma-ray spectroscopy was more effective for silt and sand prediction. Fusion greatly improved the cross-validation in most cases, indicating reduced potential of model over/under-fitting. Feature-level (RF features of micro-NIR + ROI of gamma-ray) modeled with SVR reached the best clay prediction [coefficient of determination in prediction ($R_P^2$) = 0.89, root mean squared error of prediction ($RMSE_P$) = 2.43 %], decision-level fusion with stacking methods achieved highest prediction accuracy and for silt ($R_P^2$ = 0.91 and $RMSE_P$ = 7.05 %), and sand ($R_P^2$ = 0.92 and $RMSE_P$ = 7.75 %). These findings provide valuable guidance for selecting either a single sensing technology or a fused sensing approach for accurate field soil texture estimation.

# Measuring Soil Health Using Technologies Across Scales

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**ABSTRACT**

Soil health underpins food security, climate resilience, and ecosystem services, yet its measurement remains constrained by cost, labour, and limited spatial and temporal resolution. Recent advances in sensing technologies offer unprecedented opportunities to transform soil health assessment from discrete point, plot-based measurements to continuous, scalable, and decision-ready information. This talk synthesizes advances in soil health monitoring across scales, with a primary focus on proximal soil sensing while explicitly extending the framework to areal and remote sensing to demonstrate scale transfer. The presentation will provide an overview of key technologies I have been developing and applying, including image-based soil analysis, visible–near infrared (VNIR) spectroscopy, electromagnetic induction sensing, in situ profile measurements, drone-based multispectral imaging, and satellite observations. These approaches enable the rapid estimation of physical, and chemical soil health indicators from the sample and profile scale to fields, landscapes, and regions. Using selected case studies, I will illustrate how high-resolution proximal measurements can be used to calibrate and constrain models at coarser spatial scales, allowing soil health information to be meaningfully transferred across sensing domains. By explicitly linking proximal, areal, and remote sensing observations through scale-aware modelling and data integration, this work demonstrates how soil health monitoring can move beyond isolated measurements toward integrated, multi-scale frameworks. Such approaches are essential for supporting precision management, regional soil health reporting, and policy-relevant monitoring systems.

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# Accuracies and costs of prediction and mapping soil properties using proximal sensors: A systematic review

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## ABSTRACT

We provide an overview of the accuracy of soil property predictions using the most common proximal sensing (PSS) techniques in precision agriculture (PA), both standalone and in combination with one another or with environmental covariates. Based on 114 scientific papers, we evaluate the accuracy of soil property estimates by calculating the normalized root mean square error (NRMSE) using RMSE values and the range of the predicted soil property. Soil properties, PSS techniques, covariate types, and the model employed for predictions are the factors used to sort the accuracy results. We estimate PSS service costs using both the literature and a market study with questionnaires from private companies in PA. Our analysis indicates that diffuse reflectance spectroscopy (DRS) can estimate the greatest number of soil properties with high accuracy among the PSS techniques. Popular DRS applications include determining soil organic matter, nutrients, and soil texture. X-rayfluorescence (XRF) is the second-most popular technique for estimating soil properties. XRF is widely used in the field to determine elemental concentrations. On-the-go techniques such as electromagnetic induction (EMI) or gamma-ray spectroscopy (γ-ray) yield lower accuracy than point-based techniques. They are widely used by companies because they can delineate PA management zones in the field and are suitable for on-the-go mapping of soil properties such as mineralogy, texture, salinity, water content, cation exchange capacity, and soil depth. The combined use of PSS techniques generally doesn't outperform the singular application, although the number of samples collected for calibration and the specific combinations of sensors, covariates, and modeling techniques, when correctly applied, may enhance the predictions of soil properties using PSS techniques applied singularly. These outcomes tend to depend on local site characteristics.

According to data, the estimated cost of surveying a hectare with PSS oscillates between 15.5€/ha and 130€/ha, whereas our company survey yielded an interval of 142-362€/ha. Price variability was influenced by personnel costs, fieldwork, data and reporting, sample analysis, and equipment. Increases in final prices can be attributed to accessibility and difficulties related to fieldwork and travel to the area of interest. This work aims to serve as a References for the adoption of sensing technologies by farmers, policymakers, and companies, providing insights into the suitability of different PSS techniques for soil mapping, their associated costs, and what is available in the market. We foresee that PSS will become the standard approach for producing high-resolution maps and affordable soil property information in the future.

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# Soil drainage survey using Electromagnetic induction Sensing

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**ABSTRACT**

Soil drainage class is a major source of landscape variability in Canada and the primary criterion for differentiating soil series in the province of Ontario. Drainage differences are typically governed by topographic relief, which controls surface water redistribution, and depth to groundwater, but may also arise from internal soil stratifications. Magnetic susceptibility (MS), a measure of the extent to which a material is magnetized, is a well-established indicator of soil mineralogy due to the strong MS contributions of Fe-bearing minerals. Because the nature of Fe oxides is sensitive to redox conditions—with $Fe^{3+}$ phases exhibiting substantially higher MS than $Fe^{2+}$—MS can be used as a proxy for assessing soil drainage. This study employed frequency-domain electromagnetic induction (EMI) sensors (Dualem-21 and EM38-MK4) to map magnetic susceptibility (MS) and apparent electrical conductivity (ECa) across three topographically variable sites in Ontario. Soil cores were collected at 150 points within the three study sites and examined for redoximorphic features (i.e. gleying and mottling), to classify drainage status. Laboratory measurements of volume and mass-specific MS were obtained using Bartington MS2C and MS2B sensors on core and dried samples. Our initial analysis is focused on understanding the relationship between lab-measured MS on soil cores, inverted EMI-MS measurements and redoximorphic features. Given the speed, precision, and cost-efficiency of EMI methods relative to conventional field-based classification, EMI-derived MS offers strong potential for rapid delineation of soil drainage classes across agricultural landscapes.

# A comparative study of four color measurement methods for soil color identification and related properties prediction

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**ABSTRACT**

Soil color serves as a comprehensive indicator of soil composition and intrinsic properties and can be used to predict these properties. The identification of soil color by proximal sensing varies among and even within color measurement methods. In addition, several color space models can be used to quantify color. This poses the question as to the difference between soil color measurement methods in different color spaces, the property predictions from these, and their optimal combination. A total of 200 soil samples from China, 80 from Guizhou Province and 120 from Hunan Province, were used to address this question. The color of these samples was measured by four different methods: subjective visual estimation, a smartphone, a Nix Pro2 colorimeter and an ASD spectrometer. The color difference in CIEL*a*b* color space, defined as (ΔEab), between these methods was quantified using the National Bureau of Standard (NBS) unit. Five color space models, including RGB, HIS, CIEL*a*b*, CIEL*c*h*, and CIEL*u*v*, were used to quantify soil color parameters defined by each model. These parameters were then used to predict the color-associated properties soil organic matter (SOM) and free iron concentrations (FI). Stepwise multiple linear regression (SMLR), back propagation neural network (BPNN) and partial least squares regression (PLSR) models were built to make these predictions. The color difference between the Nix Pro2 and smartphone was the smallest (ΔEab = 2.66 NBS, considered “noticeable”), while significant systematic differences were found between ASD and the other methods (ΔEab 23.48 to 25.51 NBS, “very much”). Using the visible spectra measured by the ASD as input to the PLSR model as a baseline, the ratio of performance to interquartile range (RPIQ) range for SOM prediction by other sensors and models varied from 2.90 to 3.43, while for FI, it ranged from 3.07 to 3.93. Different methods had quite different prediction performances. The ranks were Nix Pro2 > smartphone > ASD > subjective visual estimation, PLSR > BPNN > SMLR for SOM, and smartphone > Nix Pro2 > ASD > subjective visual estimation, PLSR > SMLR > BPNN for FI. Brightness-related color parameters (R, h* and L*) are recommended for SOM prediction, and yellow- and red- related parameters (S and b*) for FI prediction. The Nix Pro2 and smartphone are recommended as portable and cost-effective instruments for proximal soil sensing.

# Comparison of mid–infrared and visible/near–infrared spectroscopy of moist–intact cores and dry–ground soils for soil property prediction

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**ABSTRACT**

Mid–infrared spectroscopy (MIR) has shown great potential in soil health monitoring, but it is typically confined to laboratory measurements on dry–ground soils. To systematically evaluate the predictive performance of different spectra for key soil health indicators across the 0–100 cm profile in the Northeast Black Soil (Mollisols) region of China, this study assessed attenuated total reflectance (ATR) MIR spectroscopy on moist–intact soil cores (0–100 cm) and compared it with visible and near–infrared (VNIR) spectra on moist cores and with conventional dry–ground MIR and VNIR. Forty–nine cores (490 subsamples) were collected from Lishu County, Jilin Province, China. Organic matter (OM), total nitrogen (TN), available nitrogen (AvN), available phosphorus (AvP) and cation exchange capacity (CEC) were measured, and models were built using partial least squares regression (PLSR), support vector machines (SVM) and long short–term memory networks (LSTM). Validation strategy strongly affected estimated generalization: sample–based splits were optimistic, whereas core–based splits provided realistic performance. Under core–based validation, moist–intact ATR–MIR predicted OM ($R^2$ = 0.59, RMSE = 4.90 g/kg), TN ($R^2$ =0.51, RMSE = 0.29 g/kg) and CEC ($R^2$ = 0.75, RMSE = 3.60 cmol/kg), while AvN and AvP were not consistently predictable. Across spectra, performance ranked moist–intact MIR<moist–intact VNIR<dry–ground VNIR<dry–ground MIR. LSTM performed best with dry–ground MIR, whereas PLSR provided the most robust baseline across spectra. Models calibrated only on shallow layers (0–40 cm) did not stably predict deeper properties, reinforcing the need for full–profile measurements. Overall, while dry–ground MIR yielded the highest accuracy, the moist–intact MIR approach provided acceptable accuracy, acquiring molecular fingerprinting information without labor–intensive drying and grinding. ATR–MIR on moist–intact cores provides a foundation for extending MIR toward field–relevant workflows for rapid assessment of soil health indicators relevant to nutrient management and environmental protection.

**Acknowledgments**

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# Dynamic inversion of soil salinity in farmland across the Hetao Plain of China based on a spatiotemporal fusion algorithm (2000–2024)

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**ABSTRACT**

Accurate monitoring of the spatiotemporal dynamics of soil salinity is imperative for achieving sustainable utilization of limited farmland resources, especially in arid regions. However, current studies disproportionately focused on short-term soil salinity inversion with a single remote sensing data source, lacking comprehensive analysis of long-term evolution. The aim of this study was to investigate the spatiotemporal patterns of soil salinity in farmland of the Hetao Plain in northern China across seven stages (2000–2024) based on high-precision mapping. A deep learning framework for multi-source remote sensing data fusion was proposed to fuse MODIS images with Landsat 5/7/8/9 and Sentinel-2 images, generating two high-spatiotemporal-resolution surface reflectance datasets. Three inversion models of soil salinity were developed based on machine learning algorithms by incorporating salinity indices, environmental covariates, and ground-truth measurements. The measured soil salt content ranged from 0.39 to 17.38 $g \cdot kg^{-1}$, indicating pronounced spatial heterogeneity of salinity. Deep learning-based image fusion successfully balanced temporal continuity and spatial detail across different sensors. The convolutional neural network achieved higher accuracy than two conventional machine learning models (support vector machine and random forest), yielding the greatest $R^2$ value for the validation set (0.884). Digital mapping results revealed that the area of non-saline soils continued to expand over time. While periodic variations occurred in the areas of slightly and moderately saline soils, there were noticeable reductions in the areas of heavily and extremely saline soils. Transfer matrix analysis revealed stepwise transitions of soil salinity between adjacent classes, indicating declines in salinization levels. The findings indicate that soil salinity in farmland of the Hetao Plain has decreased over the past two decades, despite substantial variations in localized areas. This study provides robust methodological support for large-scale monitoring of farmland salinization and the development of soil salinity prediction models.

**Keywords:** Soil salinization; Multi-source satellite data; Environmental covariates; Convolutional neural network; Deep learning framework; Spatiotemporal evolution

# Monitoring soil arsenic content in densely vegetated agricultural areas using UAV hyperspectral, satellite multispectral and SAR data

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**ABSTRACT**

Accurate and effective monitoring of potentially toxic elements (PTEs) in soil across vast regions is crucial for environmental modeling and public health. While remote sensing (RS) technology provides a promising approach by detecting soil spectrum, dense and persistent vegetation cover in subtropical agricultural areas hinders acquisition of bare soil signals, limiting soil PTEs monitoring. To address this challenge, the present study proposed an innovative method for monitoring soil arsenic (As) content by using vegetation characteristics retrieved from RS data as proxy variables, given soil-vegetation interactions. The method was evaluated in a densely vegetated cropland of southern China, where 104 surface soil samples were collected. Vegetation in formation was extracted both individually and synergistically using time-series Sentinel-2 multispectral and Sentinel-1 synthetic aperture radar (SAR) images throughout the entire growing season, and an unmanned aerial vehicle (UAV) hyperspectral image during the crop maturity. Multiple machine learning algorithms, including Random Forest, Support Vector Regression, CatBoost, and Stacking were applied to model the relationship be tween soil As and vegetation variables. The SHapley Additive exPlanation (SHAP) technique was introduced for identifying key variables and corresponding thresholds indicating significant accumulation of soil As. Results showed that time-series satellite-multispectral images outperformed other single RS data types in terms of pre diction accuracy. Moreover, the synergy of optical and SAR images significantly improved model accuracy. Particularly, the combination of time-series satellite multispectral and SAR data using the stacking algorithm achieved the best results, with a coefficient of determination (R 2 ) of 0.71 and a root mean square error (RMSE) of 20.22 mg/kg. Key predictive variables included red-edge vegetation index (RENDVI3) on August 7 and May 26, and the blue band on October 26, with values below 0.018, 0.013 and 0.052, respectively, indicating the As accumulation in soil. In summary, the proposed method of using multiple RS data to retrieve vegetation char acteristics for inferring soil PTEs in densely vegetated areas was convenient, cost-effective, and reliable, offering new insights and technical support for environmental monitoring.

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# Mapping mollic epipedon thickness via ground-penetrating radar based on the combined method of Variational Mode Decomposition and Average Envelope Amplitude

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**ABSTRACT**

Accurate monitoring of mollic epipedon (ME) thickness, especially in sloping farmland, is of great significance for preventing soil erosion and promoting sustainable agriculture in Mollisol area. Ground penetrating-radar (GPR) provides an approach for continuously and non-destructively acquiring the information of soil horizon thickness. However, traditional GPR signal processing methods are susceptible to noise interference when locating soil horizon interfaces. Additionally, it remains challenging to accurately estimate the electromagnetic wave velocity due to the high spatial heterogeneity of natural soil. In this study, we proposed a combined GPR signal processing method of Variational Mode Decomposition (VMD) and average envelope amplitude (AEA), termed VMD–AEA, to investigate the ME thickness. And a GPR survey of 1.5 ha sloping farmland in the Mollisol region of Northeast China was conducted to verify the method. The noise of GPR signals was reduced using the VMD method, and then the instantaneous frequency of the denoised signal was extracted via the Hilbert transform. Subsequently, the maximum value of the instantaneous frequency was picked up through peak detection to automatically locate the ME interfaces. The results showed that the automatically located ME time-domain interfaces matched the actual interfaces marked by pre-buried steel pipes. The time-domain positions of the ME interface along survey line 1 fluctuated around 10 ns. In addition, to continuously acquire the wave velocity, a dielectric constant model was established based on the correlation between the AEA values of GPR signal and the measured dielectric constant. As expected, there was a significant negative correlation between the dielectric constant and the AEA value ($R^2 = 0.92$). The ME thickness obtained by the VMD–AEA method was consistent with the measured thickness through soil profile method, with the absolute error and relative error within 5 cm and 10%, respectively. This study proposed a novel method for automatically, continuously, and accurately obtaining the ME thickness and demonstrated its potential in the protection and utilization of Mollisol.

**Acknowledgments**

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# Hybrid Deep Learning for Soil Property Prediction Using Vis-NIR Spectroscopy

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**ABSTRACT**

Rapid and accurate acquisition of soil property is crucial for precision agriculture, ecological protection, and scientific research. This study proposes and evaluates two hybrid deep learning frameworks to enhance the effectiveness of visible-near-infrared (vis-NIR) spectroscopy in soil property estimation.

Study 1: To address the challenge of simultaneous multi-property estimation, this paper constructed a model based on the Multi-gate Mixture-of-Experts (MMoE) network. Utilizing vis-NIR spectral data from 17,272 mineral soil samples in the LUCAS database, the model achieved high-precision simultaneous estimation of ten soil properties. Compared to the traditional shared-bottom multi-task convolutional neural network, MMoE can effectively distinguish and extract both common and unique spectral features of different properties, reducing the RMSE by 3%–48% and increasing the $R^2$ by 1%–119%. The study also found that a data augmentation technique stacking multiple spectral pre-processing methods significantly improved model performance (reducing RMSE by 14%–28%), while the Competitive Adaptive Reweighted Sampling (CARS) method for extracting feature spectra showed limited effectiveness in modeling.

Study 2: To mitigate the impact of in-situ spectral measurement errors and optimize model architecture, we developed an automated optimization framework for hybrid deep learning models based on Bayesian Optimization combined with Hyperband (BOHB). Taking the estimation of soil organic matter using 670 soil samples from the Nanning region of China as a case study, a systematic comparison was conducted between two hybrid architectures: CNN-LSTM and LSTM-CNN. The results indicate that when the sample size is below 600, the advantage of hybrid models is not pronounced. However, after automated hyperparameter optimization by BOHB, their accuracy significantly surpasses that of single deep learning models, Partial Least Squares Regression, Random Forest, and other traditional methods.

In summary, the MMoE and the automated optimization framework for hybrid deep learning models developed in this study provide methodological References for the efficient and accurate estimation of soil properties.

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# Advancing Soil Health Monitoring Using Proximal VIS–NIR and MIR Spectroscopy Integrated with Multivariate Modeling

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**ABSTRACT**

Conventional laboratory-based soil analysis, though accurate, is often time-consuming, labor-intensive, and expensive, especially when large spatial datasets are required for soil fertility evaluation and soil health assessment. In this context, proximal soil sensing using visible–near infrared (VIS–NIR) and mid-infrared (MIR) spectroscopy has emerged as a rapid, non-destructive, and environmentally sustainable alternative for soil characterization. The present investigation was undertaken to evaluate the potential of proximally sensed soil spectral data as a reliable proxy for conventional soil analysis, with special emphasis on hyperspectral modeling using VIS–NIR and MIR regions. The study was conducted in the Varanasi region of eastern India, representing diverse land-use systems and soil-forming environments. A total of 300 geo-Referencesd surface soil samples (0–15 cm) were collected from rice wheat cropping systems and upland vegetable growing areas following standard sampling protocols. Soil samples were processed and analyzed for key chemical attributes such as pH, electrical conductivity (EC), organic carbon (OC), available phosphorus and potassium using standard laboratory methods. Spectral reflectance measurements were recorded under controlled laboratory conditions. VIS–NIR spectra (350–2500 nm) were acquired using a FieldSpec Pro spectroradiometer, while MIR spectra (2500–25,000 nm) were obtained using an Alpha-MIR spectrometer. Various spectral preprocessing techniques were evaluated; however, raw reflectance and absorbance-transformed spectra generally provided comparable or superior predictive performance across soil properties After removal of spectral outliers, 280 soil samples were used for model development. Prediction models were developed using Partial Least Squares Regression (PLSR), Random Forest, Support Vector Regression, and Multivariate Adaptive Regression Splines, with 70% of the data used for calibration and 30% for validation. Among the modeling approaches, PLSR consistently showed superior performance for simultaneous prediction of multiple soil properties. VIS–NIR spectroscopy performed better for pH, EC and available potassium whereas MIR spectroscopy showed higher accuracy for organic carbon and available phosphorus. Overall, the study demonstrates that VIS–NIR and MIR spectral data can serve as reliable proxies for conventional soil laboratory analysis. The complementary nature of these spectral regions highlights their potential for rapid, cost-effective, and large-scale soil assessment, supporting precision agriculture, soil health monitoring, and sustainable land management.

Keywords: Hyperspectral sensing; Mid-infrared spectroscopy; Multivariate Modeling, Soil health; Visible-near-infrared spectroscopy.

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# Identification of Alkalized Horizons Using Ground Penetrating Radar in Typical Saline-Alkali Areas of the Songnen Plain

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**ABSTRACT**

The alkalized horizon is a critical barrier layer in saline-alkali soils, directly governing root development and water-salt dynamics. Accurately identifying and quantifying its spatial distribution remains a major challenge due to its high heterogeneity. This study employed Ground Penetrating Radar (GPR) combined with the CatBoost machine learning algorithm to predict the spatial distribution of the alkalized horizon in typical soda saline-alkali soils of the Songnen Plain. Data were collected along ten survey lines containing 21 validation points. GPR signal features were extracted using Full Waveform Inversion (FWI) and wavelet transform, with key features subsequently selected by integrating CRITIC, Random Forest (RF), Mutual Information (MI), and Coefficient of Variation (CV) methods. Machine learning was applied to quantify the relationships between these key radar features and soil pedogenic characteristics. Model validation using the 21 independent points yielded robust performance, with all lines achieving a Kappa coefficient > 0.5 and an AUC value > 0.7. SHAP analysis revealed that dielectric constant and pedogenesis-related features were the dominant factors controlling the spatial variation of the alkalized horizon. This integrated GPR-ML framework provides an efficient, reproducible solution for the intelligent mapping of saline-alkali horizons. It also offers a valuable methodological References for the spatial modeling and characterization of subsurface layers using GPR, demonstrating significant application potential for saline-alkali land assessment and cultivated land quality evaluation.

# Quantitative Monitoring and Inversion of Soil Moisture Content Based on Ground Penetrating Radar: Progress, Methods, and Prospects

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**ABSTRACT**

Soil moisture content (SMC) is a critical physical parameter that regulates the hydrological cycle, agricultural productivity, and ecosystem health. Ground Penetrating Radar (GPR) can indirectly and rapidly invert soil dielectric constant by analyzing the dynamic characteristics (such as wave speed, amplitude, and frequency) of electromagnetic wave propagation in the subsurface medium, thus enabling the estimation of SMC. This technique effectively bridges the spatial scale gap between point-scale measurements and satellite remote sensing observations. The crux of GPR inversion for SMC lies in establishing a reliable physical relationship between the volumetric water content of soil and its dielectric constant, which is primarily controlled by soil moisture. Based on different data acquisition methods and signal processing strategies, mainstream inversion approaches can be categorized into several types: methods based on wave speed/travel time analysis, methods utilizing dielectric constant-water content relationship models, methods based on amplitude attenuation characteristics, methods based on spectral analysis, and integrated methods that couple hydrological models, fuse multi-physical field data, and collaborate with remote sensing data. However, GPR still faces several key challenges in the quantitative inversion of SMC. Firstly, soil dielectric characteristics are not only influenced by moisture content but also significantly depend on various factors such as soil texture, bulk density, clay mineral composition, organic matter content, salinity, and temperature. Secondly, the uncertainties in GPR inversion results stem from several complexities, including data acquisition noise, limitations of the inversion algorithms, physical model mismatches, and the spatial heterogeneity of SMC itself. Additionally, scale matching and data fusion present challenges in practical applications, especially regarding how to derive spatial averages of SMC that effectively represent remote sensing pixel scales, which requires further methodological exploration. Currently, research in this field is gradually shifting from method development to enhancing accuracy, quantifying uncertainty, deeply integrating multi-source data, and optimizing solutions for specific application scenarios. GPR technology is poised to provide solid technical support for achieving more precise and intelligent monitoring and management in areas such as sustainable water resource management, food security production, resilience enhancement of infrastructure, and ecological environmental protection.

# Prediction of soil organic matter using visible–near-infrared spectroscopy combined with textural hand-feel determination

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**ABSTRACT**

Timely and accurate estimation of soil organic matter (SOM) is vital for monitoring soil fertility and enabling precision management. This study investigates how combining soil texture data with visible and near-infrared (Vis-NIR) spectroscopy can improve SOM prediction under both laboratory (dry) and in-situ (moist) conditions. We also identify which soil properties cause the most significant differences between dry and moist spectral readings. Four modeling strategies were compared: 1) Pure Spectra (using Vis-NIR data alone), 2) Texture Class and 3) Texture Merged (integrating quantitative clay, silt, and sand content), and 4) Texture Dummy (integrating categorical texture classes determined by hand feel). We used the Cubist algorithm to assess the contribution of different soil properties, while Partial Least Squares Regression (PLSR) and Random Forest (RF) models were used for SOM prediction. Results show that soil texture was the most significant factor driving the differences between the moist and dry spectra. Texture was also the primary variable explaining the prediction errors (residuals) when using spectra alone. Critically, incorporating simple, field-assessed texture data via the Texture Dummy strategy significantly improved SOM prediction accuracy compared to models relying on pure spectra, with the highest R2 increasing from 0.65 to 0.78 and from 0.79 to 0.86 and the root mean square error decreasing from 5.73 to 4.56 g kg−1 and from 4.47 to 3.62 g kg−1 for wet and dry samples, respectively. The Texture merged strategy provided a modest improvement (R2 increasing from 0.63 to 0.66 using in situ spectra), while the Texture class strategy showed the lowest performance, with slightly reduced R2 values for both dry and in situ spectra. The accuracy achieved using the Texture dummy strategy with in situ spectra (R2 = 0.76, LCCC = 0.86) was comparable to that of the general model developed from laboratory spectra (R2 = 0.79, LCCC = 0.88). Our findings demonstrate that incorporating the Texture class determined by hand-feel can effectively guide spectral techniques, enhancing the potential of vis–NIR spectroscopy in rapid estimation of SOM. However, further verification is needed using soils from a wider range of areas and larger spectral libraries, as well as other spectroscopic techniques across different wavelength ranges.

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# The use of low-cost spectrometers to predict key soil properties for digital soil mapping in South Sumatra, Indonesia

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**ABSTRACT**

Detailed digital soil mapping requires dense soil data and observations. However, it is labor-intensive and time-consuming to analyse many soil properties. While the advent of visible and near-infrared (Vis-NIR) spectroscopy offers a time- and cost-effective approach for measuring soil properties, the use of alternative lower cost Vis-NIR spectroscopy for soil properties prediction in digital soil mapping remains limited. This study aims to test the quality of lower-cost Vis-NIR spectrometers in estimating key soil properties in the humid tropical region. We collected soil samples from 291 sites, each with three depths (0-10, 10-20, and 20-40 cm) from Central Lampung, Indonesia based on *k-means* clustering of environmental covariates. We selected 58 sites (174 soil samples) from all clusters as data set for chemical-physical soil analysis and spectra calibration. We tested two emerging spectrometers which are available at a lower cost: a Vis-NIR spectrometer (350-1020 nm) and a NIR-SWIR (900-2500 nm). The samples were scanned under two conditions: field moisture and ground and air-dried. As a comparison, we used the ASD spectrometer (350-2500 nm). The data set was randomly split by sites into 70% training and 30% as test set. We applied Savitzky-Golay smoothing and a second-order polynomial for preprocessing. We investigated several soil properties predictions namely organic carbon, pH, sand, and clay. Prediction models were constructed with partial least squares regression (PLSR) and Cubist tree model. In general, the Vis-NIR-SWIR spectra perform quite good across all properties. The $R^2$ of PLSR ranges from 0.38 to 0.67 for Vis-NIR, 0.50 to 0.67 for NIR-SWIR, as compared to 0.62 to 0.75 for ASD. Cubist model performed slightly better for several properties and conditions. Our findings indicate the prediction of lower-cost Vis-NIR-SWIR spectrometers both under field and dried-sieved condition is comparable to ASD spectra and can be used to estimate soil properties for soil mapping in humid tropical regions.

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# Comparison of mid and near infrared spectroscopy in predicting stable isotope values (δ 13C and δ15N) of tropical soils in Madagascar

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**ABSTRACT**

Stable isotope analyses, particularly those involving carbon and nitrogen ($\delta^{13}C$, and $\delta^{15}N$), provide valuable insights into soil organic matter and nitrogen dynamics and pathways. Such studies are essential for understanding ecosystem functioning by tracing vegetation changes over time through the $\delta^{13}C$ and $\delta^{15}N$ soil profiles. In Madagascar, such studies under open ecosystem areas (OEA) are crucial towards further effective reforestation guidance. However, isotopic measurements remain challenging due to the lack of isotope ratio mass spectrometer (IRMS) infrastructure and the high cost of analyses. To overcome these limitations, the use of spectroscopy techniques either in mid-infrared (MIR) or near-infrared (NIR) could offer a rapid and cost-effective alternative method for future investigations. This study aims to evaluate the potential of MIR and NIR spectroscopy to predict $\delta^{13}C$ and $\delta^{15}N$ values in OEA tropical soils of Madagascar.

Soil samples (n = 800) were collected throughout 3 protected areas located in the north (Ankarafantsika (AF) under ferruginous soil, n = 257), mid (Ambohitantely (AT) under ferrallitic soils, n= 278,) and the South-east (Ivohiboro (IV) under ferrallitic soils, n= 265) of Madagascar across 5 depth layers: 0-10 cm, 10-20 cm, 20-30 cm, 50-60 cm and 80-90 cm and considering 3 land use types: natural forest (Dry in AF, altitude humid for IV and AT), shrubland and grassland. Soil samples were dried and ground at 0.2 mm and analyzed by elemental analyzer-IRMS to get $\delta^{13}C$ and $\delta^{15}N$ values. Field-spec analyzer and PerkinElmer FT-IR Spectrometer Frontier were also used for the acquisition of NIR spectra (NIRS) and MIR spectra (MIRS), respectively. The isotopic modelling was achieved with locally weighted partial least squares regression (LW-PLSR) on MIRS and NIRS spectra separately. For both spectral ranges, the same samples were used for calibration (n = 600, selected for spectral representativeness) and for validation (n = 200). The prediction accuracy of the models was evaluated on the validation subset using the coefficient of determination ($R^2$) and the ratio of performance to deviation (RPD). The higher $R^2$ (>0.8) and RPD were (>2), the more accurate prediction model was.

Model based on MIRS yielded excellent prediction for $\delta^{13}C$ ($R^2$ of 0.80 and RPD of 2.22) compared to the NIRS ($R^2$ of 0.40 and RPD of 1.21). For $\delta^{15}N$ the NIRS ($R^2$ of 0.55 and RPD of 1.48 in validation) outperformed MIRS ($R^2$ of 0.42 and RPD of 1.41 in validation)) with poor prediction for both spectral ranges.
The better $\delta^{13}C$ performance of MIRS reflects its sensitivity to specific molecular vibrations associated with carbon functional groups, while the relatively higher $\delta^{15}N$ prediction from NIRS may result from weak N–H and amide overtones that correlate indirectly with nitrogen content.

These findings highlight MIR as a promising, cost-effective alternative to traditional isotopic analysis for monitoring carbon dynamics in Madagascar.

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# Determination of Nitrogen in Maize Plant Using Near Infrared Spectroscopy and Partial Least Squares Regression

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## ABSTRACT

Rapid detection of nitrogen in maize leaves is crucial for predicting precisely fertilizer requirements and ensuring efficiency and sustainability of production. In this research, near infrared spectroscopy had been examined for its potential for the diagnosis of the critical and insufficient levels of nitrogen element through dried maize leaf. Sixty-one samples of Dong-dan1331 cultivar were collected with whole plant at the 3- to 4-leaf stage and with the entire first mature leaf below the whorl before tasseling, respectively, from the pot experiment. The samples were dried in a 70°C forced air drying oven and finely ground, sieved through 0.5 mm sieve prior to chemical analysis and NIR scanning. Nitrogen in dried ground samples was determined by the vario EL III elemental analyzer (Elementar Analysensysteme GmbH, Germany). NIR spectra were measured by a MPA Multi Purpose FT-NIR Analyzer (Bruker Optics, Germany) in the reflectance mode. The scanning was performed by a OPUS program. Spectral data were exported into the Unscrambler software v.6.1 (Camo AS Trondheim, Norway) using the JDX formatted files for calibration development. Partial least squares regression (PLS) was used to establish the relationship between the spectra and the nitrogen nutrient content in maize leaves. Spectral pretreatment methods, such as conversion to absorbance, multiplicative scatter correction (MSC), mean normalization, moving average smoothing (with three adjacent spectral datapoints), Savitzky-Golay smoothing (with 7 averaging datapoints and a polynomial order of two), Norris first derivative (with a segment of 5 datapoints and a gap of 4 datapoints), Savitzky-Golay first derivative (with the convolution interval of 5 datapoints and a polynomial degree of 2), Savitzky-Golay second derivative (with the convolution interval of 13 datapoints and a polynomial degree of 2), and, or, a combination thereof, were used through the Unscrambler 6.01 software before calibration. PLS calibrations were developed with a full cross validation (leave-one-out validation) procedure. The parameters used to evaluate the quality of the calibrations were the coefficient of determination for calibration (Rc2) and for validation (Rv2), the root mean square error of cross validation (RMSECV), the root mean square error of calibration (RMSEC) (Esbensen et al., 1994), ratio of performance deviation (RPD) (Williams and Sobering, 1993; Chang et al. 2001) and the ratio error range, RER(Williams and Sobering, 1996). No sample outlier was excluded when making these calibrations.

The near-infrared spectroscopy combined with partial least squares (NIRS-PLS) model developed in this study not only demonstrates the feasibility of quantitative nitrogen analysis in corn, but also reveals the profound impact of spectral preprocessing on model performance through detailed parameter comparisons. Furthermore, it highlights the similarities and differences in model performance across samples from different growth stages. High coefficients of determination (R2>0.92) for seedling and tasseling samples were observed between the nitrogen contents determined by the elemental analyzer and those estimated by the FT-NIR Analyzer.All models achieved RPD values significantly above 3.0, strongly demonstrating their high accuracy and stability in samples. All models in this study demonstrated RER values above 20, with the highest reaching 31.33, further confirming reliable predictions across the entire nitrogen content range of test samples. In summary, the models developed in this study achieved meeting the needs for rapid and non-invasive diagnosis of maize nitrogen nutrition status.These results confirm that NIRS enables rapid and accurate quantitative analysis of nitrogen content in corn leaves. The optimal pretreatment method for seedling leaves was "mean normalization", which demonstrated the best performance with 6 factors (RMSECV=0.6816, RPD=5.64, RER=31.33). For the tasseling stage, the optimal pretreatment method was Savitsky-Gore first-order derivative, achieving the best results with 2 factors (RMSECV=0.8172, RPD=8.23, RER=28.02). The study reveals that the dominant factors influencing near-infrared spectroscopy vary significantly across different plant growth stages. Spectral data from whole-plant seedling samples demonstrated greater complexity. In contrast, leaf samples collected during the tasseling stage exhibited a more stable chemical composition, resulting in clearer and more distinct spectral characteristics of nitrogen content.

The study highlights the necessity of developing specific calibration models for different growth stages. Results demonstrated that by optimizing spectral preprocessing methods, near-infrared spectroscopy (NIRS) based on partial least squares regression can achieve high-precision and reliable quantitative analysis of nitrogen content in corn leaves. This provides an effective approach for rapid diagnosis of nitrogen nutrients and the foundation for subsequent nitrogen fertilizer recommendation.

**Keywords:** near infrared spectroscopy; maize; nutrient diagnosis; PLS; nitrogen.

**Acknowledgments**

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# A Vis-NIR penetrometer system for field measurement of soil organic carbon

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**ABSTRACT**

The evaluation of soil properties is labour-intensive and time-consuming. The cost of laboratory analyses thus limits the spatial resolution of sampling. Therefore, in situ measurement of soil properties such as soil organic carbon (SOC) is urgently needed. Visible and near-infrared (Vis-NIR) spectroscopy is considered a feasible alternative for field measurements. The integration of Vis-NIR spectrometers and a penetrometer to obtain measurements of soil spectra in subsoils can greatly enhance the data acquisition rate and enable higher resolution sampling. In this study, a Vis-NIR penetrometer system was used to acquire soil spectra in the field conditions. The system utilised two low-cost spectrometers which cover 350-2500 nm. The penetrometer sampled soil spectra at 2-cm intervals, and spectra from five consecutive depths were averaged to represent a 10-cm interval, corresponding to a 10-cm core sample as ground truth data. The penetrometer is attached to hydraulic sampler enabling exploration up to 1 m depth. Soil spectra were acquired under field conditions at 18 locations in New South Wales, Australia. The spectra were calibrated with 130 soil samples collected in the field. Ten-fold cross-validation using a Cubist regression tree model yielded an R2 of 0.74 and a root mean squared error of 0.21%, indicating that the penetrometer can reliably predict SOC under field conditions. This penetrometer system enables acquisition of soil spectra to depths of up to 100 cm in under 5 minutes, facilitating rapid determination of SOC in the field.

# A comparative study of Random Forest and Neural Network with implementation of Boruta algorithm for predicting soil properties from Visible-Near Infrared spectra

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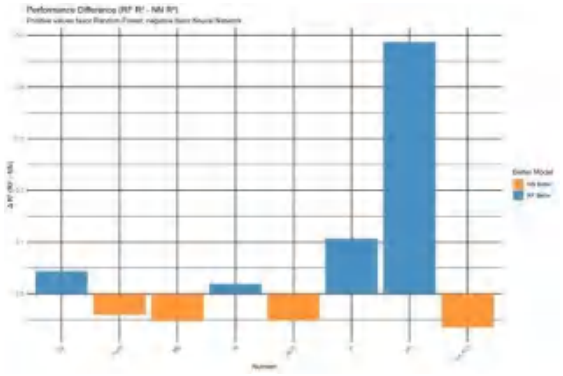
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**ABSTRACT**

Efficient monitoring of soil fertility and plant health is essential for sustainable agriculture. Visible and near-infrared (Vis-NIR) spectroscopy offers a rapid and non-destructive alternative to conventional soil analysis [Viscarra Rossel et al., 2006]. This study investigates the relationship between bare soil spectral reflectance curves and key soil properties: pH ($H_2O$ and KCl), content of organic matter, nitrogen (N), nitrate ($NO_3$), calcium (Ca), magnesium (Mg), and phosphorus (P). Specifically, by comparison the performance of a Random Forest model against an Artificial Neural Network. We collected a total of 30 soil samples from agricultural land (Moscow region, Vnukovsky district), represented by glossic Retisols. Diffuse reflectance spectra (325-1075 nm) were acquired using a FieldSpec HandHeld 2 spectroradiometer. Spectral preprocessing included Savitzky-Golay smoothing, Standard Normal Variate transformation, and first-derivative analysis. For automated feature selection to identify the most relevant wavelengths the Boruta algorithm was employed, which reduced the initial set of 741 wavelength to the range from 10 to 13 key wavelength without losing model accuracy. Comparative analysis revealed wavelength selection patterns across nutrients: organic matter content and related nutrients (N, NO3) showed stronger selection in visible regions (590-624 nm range), while mineral nutrients (Ca, Mg) and pH exhibited importance across broader spectral ranges (600-1050 nm). At the same time, some wavelengths (namely, 604, 605, 606, 607 nm) were same for several soil properties such as nitrogen, organic matter content and pH (both $H_2O$ and KCl), which demonstrates the general relationship between all important agronomic soil properties. The predictive performance for all properties was quite good (Pic. 1). The Random Forest model demonstrated superior performance for predicting nitrogen ($R^2 = 0.94$, RMSE = 0.01) and calcium ($R^2 = 0.92$, RMSE = 0.04) content. The ANN model achieved its highest accuracy for magnesium content ($R^2 = 0.97$, RMSE = 0.24). However, pH ($H_2O$) and phosphorus content showed lower predictability ($R^2 < 0.88$) with both methods, likely due to their complicated relationship with spectral features. This study demonstrates that Vis-NIR spectroscopy coupled with machine learning is a powerful tool for predicting several key soil properties.



Pic. 1

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# Transferability of Global Spectral Models for Local Soil Organic Carbon Predictions: Effects of Spiking on Model Performance

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## ABSTRACT

Visible near-infrared (vis-NIR) spectroscopy is a rapid, non-destructive, environmental-friendly, and cost-effective technique well suited for analyzing key soil properties. Over the years, numerous studies have used vis-NIR spectroscopy to generate huge amounts of soil spectral data, leading to the development of numerous soil spectral libraries (SSL) at global, national, and regional scales. These SSLs serve as large databases and can be used for both qualitative and quantitative soil analysis. With the advancements in machine learning (ML) and artificial intelligence, these can be leveraged to monitor soils at the local or farm scale. However, the transferability of such models can be challenging due to high heterogeneity and spatial and temporal variability in soil samples. Thus, the objective of this work was to investigate and improve the effectiveness of the Canadian Prairie Soil Spectral Library (CPSSL) to predict soil organic carbon (SOC) at three farms (local datasets) in the Canadian prairies. A global model for the Prairies was first created using 7924 samples from 2305 locations across the three Canadian prairie provinces, namely, Alberta, Saskatchewan, and Manitoba. This global model was then spiked with samples from the three local datasets (n = 130, 389 and 798, respectively). We used different spiking strategies to select the best spiking subset and spiking ratio. Different regression based and ML models were developed to predict SOC. Based on preliminary analysis, we observed that spiking the global model with 20% local samples significantly improved the local predictions (28% increase in coefficient of determination, and 17.4% decrease in root mean square error). Further analysis will focus on the spatial distribution of the samples to be used for spiking and the use of different combinations of feature selection algorithms and models to improve the predictability of the global model for local datasets. Another aspect of the study will investigate the use of subsets of the global dataset, based on soil type, management practices, and spectral similarities to improve the adaptability of global models for local predictions. Preliminary results will be presented and highlight the immense potential of a SSL for soil monitoring at local scales. This will help to fill soil data gaps and improve accessibility to critical soil information.

# Standardized Protocol for Soil Organic Matter Prediction using Vis-NIR Spectroscopy- A Meta-Analysis

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**ABSTRACT**

The increased interest and adoption of precision agriculture techniques underscore the urgent need for spatially and temporally explicit soil data. Over the past few decades, spectroscopy has emerged as an effective tool for soil analysis. Numerous studies have employed visible near-infrared (vis-NIR) spectroscopy to quantify various soil properties. Amongst these, soil organic matter (SOM) has gained prominence in the research community due to the significant role it plays in agricultural systems, climate change, and its influence on a wide range of soil properties. However, there is no standard protocol for soil spectral analysis and hence the procedure used varies across studies, thus presenting obstacles in comparing and sharing the datasets and results. To address these challenges, the aim of this work is to develop an optimal standard protocol for soil spectral analysis in the vis-NIR range to predict SOM. We conducted a meta-analysis where 350 articles published from 1990 to 2024 were selected from three scientific search engines, namely Google Scholar, Web of Science and ProQuest. We collected protocol data from each of these studies and the extracted information encompassed different aspects such as laboratory or in-situ spectra collection, sampling approach, sample size, instrumentation, sample processing, spectra preprocessing, model training, and validation. This dataset provides a comprehensive overview of the wide array of methodological techniques applied across different procedural steps. Subgroup analysis was applied to observe the influence of the protocols on the performance of spectral models. Initial results highlight the major developments in the field of soil vis-NIR spectroscopy in terms of technology, accessibility, scalability, and adaptability. While it is broadly expanding, the adoption is not as uniform. Moreover, significant differences among the performance of different protocols were found. This can be attributed to the scale of the dataset, and differences in spectral acquisition and chemometrics analysis. Combining metadata with spectral data improved SOM predictability in some cases. Further analysis of this dataset will look at the best performing and most consistent protocol that can be used as a standard across different studies. This standard protocol can serve as a step towards enhancing the comparability and accessibility of soil vis-NIR spectral data.

# Carbon Assessment in Peat Soils Through Moisture-Corrected Vis–NIR Spectroscopy and Instrument Comparison

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**ABSTRACT**

Peatlands are among the largest global carbon reservoirs; but the monitoring of such areas requires rapid and reliable methods for the estimation of soil properties. Visible and near-infrared spectroscopy (vis-NIRS) is widely used for Total Organic Carbon (TOC) assessment; however, the high-water content typical of peat strongly affects reflectance under field conditions, altering spectral features and reducing prediction accuracy. This study compares the performance of two different spectrometers, the ASD LabSpec (350–2550 nm) and the Si-Ware NeoSpectra Scanner (1350–2550 nm), for analyzing Danish peat soils under variable moisture conditions. The water absorption bands at 1400 and 1900 nm are the most affected by O–H overtones, these regions were therefore used to identify and isolate moisture-related spectral variability, which was subsequently removed from the full spectra before developing TOC prediction models with the full range of both instruments.

A total of 150 peat samples were collected and scanned in triplicate with both spectrometers. All samples were measured under dry conditions, and a subset of 60 was additionally rewetted to approximately 30%, 60%, and 90% gravimetric moisture content. To mitigate moisture interferences, External Parameter Orthogonalization (EPO) was applied as a multivariate correction technique aimed at removing water-induced spectral variance while preserving TOC-relevant information. The rewetted subset is being used to build the EPO model, which will then be applied to the entire dataset to improve model robustness and reduce moisture-driven discrepancies between the two instruments.

The main objectives of this work are: (i) to quantify the differences in moisture-related spectral response between LabSpec and NeoSpectra, (ii) to evaluate the effectiveness of EPO in reducing water-induced variability by comparing spectral distances and TOC model stability before and after correction, and (iii) to assess the improvement in TOC prediction accuracy after correction. Expected outcomes include identifying which instrument is less sensitive to moisture and therefore more suitable for field measurements and supporting the development of a practical workflow that enables the use of in-field spectra without requiring laboratory drying or sample preparation. This will contribute to more consistent VIS- NIRS based characterization of organic soils and more reliable carbon assessment in peatland monitoring.

**Keywords:** Peat Soils, Spectroscopy, Total Carbon, Moisture effects, Proximal Soil Sensing

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# Spectroscopic Screening of Soil Extracellular Oxidases and Their Application in Soil Health Monitoring and Carbon Modeling

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**ABSTRACT**

Soils underpin food security, water quality, and the global carbon cycle, yet we lack fast, reliable tools to quantify the oxidative enzymes that govern how soil organic matter is stabilized or lost to the atmosphere. Measuring oxidative activities in soil is technically feasible using an *in vitro* soil enzyme assay that has been established for decades. However, the colorimetric method is time-consuming, labor-intensive, cost-inefficient and highly variable, making it impractical for large-scale or field-based monitoring. To address this challenge, we developed a spectroscopic method based on surface-enhanced Raman spectroscopy (SERS) and enabled fast and accurate monitoring of the two typical soil extracellular oxidative enzymes, horseradish peroxidase (HRP) and polyphenol oxidase (PPO). At the core of the new method, variations of SERS spectral patterns of L-DOPA are found to be a function of HRP or PPO concentrations through a partial least square (PLS) model. The model's performance remains satisfactory when applied to diverse soil samples collected in the Nashville Metropolitan area in TN, USA. In the future, we expect to generate spatially resolved real-time datasets that pinpoint potential soil health issues and empower AI-driven Microbial-Enzyme SOC modeling. Moreover, it holds potential to revolutionize real-time environmental monitoring of other environmentally relevant enzymes, such as hydrolases.

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# Comparative analysis of Vis-NIR and MIR spectroscopy for predicting soil properties and identifying minerals at smallholder cocoa farms across Papua New Guinea

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## ABSTRACT

Cocoa ranks as Papua New Guinea's (PNG) third most important agricultural export, providing livelihoods for ~2 million smallholder farmers, supporting Food Security. Recently, the condition and capacity of cocoa soils have deteriorated from inadequate nutrient management under intensified cocoa farming—with little soil monitoring and nutrient replenishment—due to resource-constraints. To rapidly and cost-effectively evaluate the condition of cocoa soils in PNG, this study presents the first comparison of visible and near-infrared (Vis-NIR) and mid-infrared (MIR) spectroscopy. We developed a spectral library by measuring 17 soil properties and spectral features from 507 soil samples collected at four smallholder cocoa farms across major cocoa production regions of PNG. Results showed that both Vis-NIR and MIR spectral features predicted over half of the soil properties with relatively high accuracy (Lin's concordance correlation coefficient ≥ 0.80), including: sand, clay, SOC, available N, available K (Vis-NIR only), exchangeable Ca, exchangeable Mg, Fe, Cu and Mn. MIR outperformed Vis-NIR in predicting soil texture and most chemical properties, while Vis-NIR provided slightly better predictions for certain nutrients—notably available K. The modelling results showed that between Cubist and partial-least-square regression (PLSR) models, Cubist models outperformed PLSR models for both Vis-NIR and MIR. Finally, MIR outperformed Vis-NIR in identifying soil minerals—such as kaolinite, gibbsite, halloysite, and calcite—using wavenumbers, making MIR the preferred spectroscopy method only when accurate mineral identification is required. These findings demonstrate Vis-NIR spectroscopy as the preferred and more practical method to effectively assess key soil properties for cocoa production—serving as a starting point for soil monitoring and nutrient management across cocoa farms in PNG—with broad applicability for soil monitoring and nutrient management in other resource constrained environments.

# Estimation of Soil Inorganic Carbon Based on Visible Near Infrared Reflectance Spectroscopy Absorption Depth

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## ABSTRACT

Soil inorganic carbon (SIC) mainly occurs in the form of $CaCO_3$ and is essential in stabilizing the soil carbon pool and maintaining soil ecological functions. Previous studies have demonstrated that soil $CaCO_3$ content can be effectively estimated from visible-near infrared (Vis-NIR) reflectance spectroscopy using partial least squares regression and machine-learning approaches. However, these approaches are often methodologically complex and computationally intensive, which limits the applicability of simpler linear regression methods. Moreover, few studies have directly estimated calcium carbonate mass density from Vis-NIR reflectance spectroscopy.

A total of 43 soil profiles were collected from Cixi, Dongtai, Sheyang, and Tongzhou. Samples were obtained at 10 depth intervals within each profile. Figure 1 illustrates the procedures for soil property determination, spectral processing, and model development and evaluation.

The performance of different models for calibration and validation is presented in Table 1.

Results indicate the 2330-2360 nm spectral region exhibited the strongest correlation with $CaCO_3$ content; thus the maximum absorption depth within this range was defined as the absorption peak (AP). Models based on latent variables (LVs) combined with nonlinear regression achieved consistently high accuracy across both individual sites and the combined dataset (validation $R^2$ generally > 0.9). In contrast, AP-based linear models performed well at individual sites but showed substantial degradation when applied to the combined dataset (validation $R2 \approx 0.3$). Estimation accuracies for SICC*i* and SICD*i*cm were highly consistent. The strong correlation between SICC*i* and SICD*i*cm provides a physical basis for estimating SICD*i*cm using Vis-NIR reflectance spectroscopy (Figure 2).

In conclusion, the AP-based linear model represents a rapid and cost-effective alternative for localized SIC estimation. Direct estimation of SIC density at the one-centimeter soil layer using Vis-NIR reflectance spectroscopy was shown to be feasible.

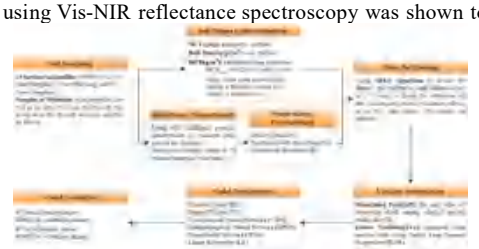


Figure 1 Steps for estimation and validation for SICCi and SICDicm using Vis-NIR reflectance spectroscopy

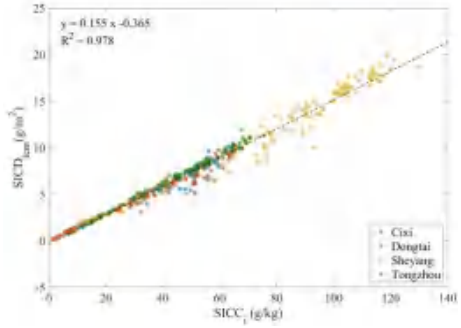
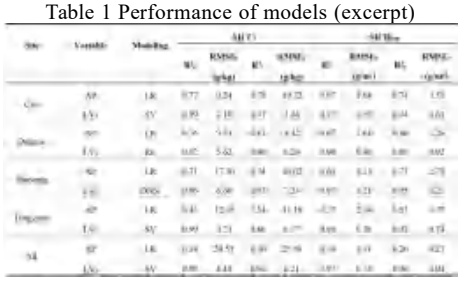



Figure 2 Scatterplot for SICCi and SICDicm

Table 1 Performance of models (excerpt)



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# Alternative Spectroscopic Approaches for Soil Analysis: A Comparative Study

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**ABSTRACT**

Soil sample archives are increasingly valuable for research, particularly for testing spectroscopy with new sensor technologies and combinations. For this study, four distinct soil datasets were obtained from the Italian national archive of CREA, Florence, and were selected to maximize pedological and geographical diversity. The first dataset consists of Cambisols from Italy, while the second and third include Luvisols from Slovenia and Calcisols from Turkey, all collected from agricultural fields covering only a few hectares, representing small-scale, intensively managed areas. The fourth dataset was chosen to capture the broadest diversity, encompassing soils from Russian Chernozems to African Lixisols, representing 30 of the 32 WRB References Soil Groups (RSG). Clay content ranges from 0.1% in Arenosols to 96% in Nitisols, with sand content and organic carbon showing similarly wide variability. Each dataset contains 50–80 samples, including topsoil and subsoil layers, ensuring a representative range of soil conditions. The study compared an emerging low-cost NIR spectrometer (Polispec, TPhotonics, 900–1700 nm, direct contact) with a more established Vis–NIR spectrometer (ASD FieldSpec 3, 350–2500 nm). Polispec spectra were integrated with CIE Lab* color coordinates obtained with a NIX 2 Spectrophotometer and converted into Munsell spectra over 380–730 nm. To minimize differences due to instrument configuration and acquisition conditions when comparing spectral data from different SSL sources, the International Soil Standard (ISS) based on Lucky Bay white sand was applied. Instrumental comparisons revealed non-constant absorbance differences, with ASD readings on average about 10% higher than Polispec, highlighting the importance of standardized References and calibration. Key soil parameters—organic carbon, clay, and sand content—were modeled using Partial Least Squares (PLS) regression with Leave-One-Out (LOO) cross-validation. Validation with Polispec data showed moderate and variable performance: clay NRMSE 13–23%, $R^2$ 0.10–0.76; sand NRMSE 10–28%, $R^2$ 0.21–0.89; organic carbon NRMSE 13–23%, $R^2$ 0.12–0.76. Integration of VIS color spectra only marginally improved organic carbon predictions. Models based on ASD spectra showed superior predictive ability: clay NRMSE 6–19%, $R^2$ 0.20–0.93; sand NRMSE 10–17%, $R^2$ 0.14–0.86; organic carbon NRMSE 17–19%, $R^2$ 0.19–0.60. Despite limited variability in range, modest estimation performances were still observed. Restricting the spectral range to 1700–2500 nm caused substantial information loss, emphasizing the importance of broader spectral coverage for reliable soil property estimation.

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# Vis–NIR Spectroscopy and Chemometrics for Soil Pollution Assessment: Challenges and Opportunities

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**ABSTRACT**

Global soil contamination represents a critical environmental challenge, with heavy metals (HM) affecting 15–20% of agricultural and urban soils worldwide. These contaminants pose exceptional risks due to their persistence, bioaccumulation potential, and direct pathways into human food systems, creating cascading effects on public health and food security. The urgent need for rapid contamination assessment has driven significant advances in visible–near infrared (Vis–NIR) spectroscopy over the past two decades. This study aims to review the current advances in chemometric approaches using machine learning (ML) and recent methodological developments in Vis–NIR instrumentation. A conceptual framework is proposed to incorporate the variability of geographical settings, soil types, and pollution sources into predictive models. The ability to estimate HM contents with chemometric approaches, using both linear and non-linear models, relies on indirect correlations with other spectrally active soil components (such as clay minerals, organic matter, iron oxides, and primary minerals) that may co-vary with HM in the 400–2500 nm range. Key methodological advances involve robust spectral pre-processing (e.g. Savitzky–Golay filtering, orthogonal signal correction, standard normal variate) to reduce noise and improve absorbance spectra (−log(R)). Pre-processing is still a matter of debate, particularly regarding how contact conditions, distance, illumination geometry, may affect spectral responses, which is critical for field (on-the-go) applications where optical geometry is uncontrolled. For many proximal sensing tasks, it is not necessary to reconstruct the full spectrum (400–2500 nm); instead, short-range Vis–NIR (e.g. 400–1700 nm or 850–1700 nm) can be exploited, although this range remains comparatively underexplored. However, HM soil contamination is typically highly skewed and spatially heterogeneous, making global prediction models difficult to calibrate, strongly site-dependent, and challenging to transfer reliably to other regions. Spectroscopic approaches for soil metals, such as portable XRF, can help to perform better when combined with Vis–NIR spectroscopy, to reduce uncertainty of the models, and the heterogeneity of the sampling. To mitigate this, partitioning strategies divide large, heterogeneous survey areas into more homogeneous sub-areas, with optimal partitions is a possible approach. Ordinary cokriging can further improve Vis–NIR prediction models (300–2500 nm) by using variables such as soil organic matter (SOM), Fe and clay contents as covariates, in combination with non-linear ML methods (RF, SVM, ANN) that often outperform classical regression approaches (MLR, PCR, PLSR). In any case, the observed relationships tend to be highly site-specific and must be transferred to new soils or regions carefully when environmental and geographic conditions differ.

# Sample Transfer Learning for Improving Field-Scale Soil Organic Matter Inversion via UAV Hyperspectral Remote Sensing

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**ABSTRACT**

Field-scale soil organic matter (SOM) inversion via UAV hyperspectral remote sensing suffers from low accuracy, primarily attributed to the challenges of intensive sampling and low SOM variability within individual plots. This study employs a sample transfer learning method to expand the calibration sample set for field-scale UAV hyperspectral inversion and improve the accuracy of farmland SOM retrieval, by extracting training samples from a large soil spectral library.

The UAV hyperspectral dataset of a red soil dryland in Jiangxi Province, southern China was designated as the target domain. At this plot, a total of 50 topsoil samples were collected, and hyperspectral data (450–950 nm) were acquired using a DJI M300 UAV equipped with a Cubert S185 hyperspectral imager. These samples were partitioned into training and test sets at a 7:3 ratio. The source domain was a soil spectral database collected from soil series surveys across multiple Chinese provinces, comprising over 5,600 genetic horizon samples from approximately 1,400 soil profiles. Spectral reflectance data (350–2500 nm) of these samples were measured with a Cary 5000 spectrophotometer.

A comprehensive similarity index was established based on landscape and spectral similarities between source domain samples and the target domain training set. Source domain samples with comprehensive similarity above the threshold and SOM content within the preset range were selected as the source domain transfer sample set. This set was then merged with the target domain training set to generate an expanded training dataset for SOM spectral inversion modeling. Given that the target red soils contain high levels of free iron oxides, which typically mask SOM signals in soil spectral reflectance, the iron removal spectral preprocessing method proposed by Qiu et al. (2025) was adopted, followed by the construction of a SOM hyperspectral inversion model using the random forest algorithm.

Results indicated that, compared with the accuracy of the inversion model built using only the target domain training set (test set: $R^2$=0.31, RMSE=1.27 g/kg), the model built on the expanded training set yielded significantly higher accuracy for field-scale SOM inversion via UAV hyperspectral remote sensing (test set: $R^2$=0.66, RMSE=0.86 g/kg).

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# Characterization of soil organic matter regarding both the structure and composition by Fourier transform infrared attenuated reflectance spectroscopy

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**ABSTRACT**

Accurate characterization of soil organic matter (SOM) is crucial for assessing soil fertility and its role in the global carbon cycle. The functionality of SOM depends not only on its total content but also on its chemical structure and composition, with stable organic matter serving as the primary functional component. Current research predominantly focuses on the total amount of SOM, lacking systematic investigation into its functional attributes. Traditional chemical analysis methods often disrupt the native structure of organic matter during extraction and measurement, and they tend to emphasize total content assessment, making it difficult to systematically elucidate the intrinsic relationship between molecular composition and stability. Therefore, this study employed in situ, non-destructive attenuated total reflectance Fourier transform infrared attenuated reflectance spectroscopy (ATR-FTIR), combined with partial least squares regression (PLSR) and multivariate statistical methods, to simultaneously obtain information on the content and structure of organic matter. The molecular structural characteristics and stability-driving mechanisms of organic matter in four typical agricultural soils in China—black soil, Fluvo-aquic soil, paddy soil, and red soil—were systematically analyzed. By performing peak fitting to extract the relative areas of aromatic C=C stretching vibration peaks at 1425, 1511, 1515, and 1660 $cm^{-1}$, a stability index (PI) was constructed to characterize the chemical stability of organic matter. The results revealed a clear inconsistency between the content and stability of organic matter across different soils. For example, black soil exhibited the highest total organic matter content but a significantly lower PI compared to Fluvo-aquic soil, indicating a lower proportion of stable components. Comparisons among different soil types further demonstrated that PI can simultaneously reflect both the "quantity" and "quality" of organic matter, addressing the limitations of traditional methods in functional characterization. By integrating spectral structural information with systematic comparisons across multiple soil types, this study provides theoretical support and methodological foundations for constructing an integrated quantity–quality evaluation system for soil organic matter.

**Acknowledgments**

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# Soil Profile Horizon Classification Integrating Point-Based Hyperspectral Data and Machine Learning Algorithms

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## ABSTRACT

Soil profiles are central to the study of pedogenesis, with their genetic horizons directly reflecting soil-forming processes. Spectral technology is widely used in soil analysis and investigation due to its advantages of speed and non-destructiveness. The ASD reflectance spectrometer can acquire continuous high-resolution spectra, capturing subtle features such as organic matter and minerals, providing reliable data support for the efficient and non-destructive identification of genetic horizons.

This study focuses on a laterite soil profile. Using an ASD spectrometer equipped with a contact probe, 40 hyperspectral samples were collected at 2.5 cm intervals along a 1-meter deep profile. After preprocessing through averaging and Savitzky–Golay smoothing, a dataset for genetic horizon identification was constructed. Principal Component Analysis (PCA) was employed for dimensionality reduction to extract key spectral features, reduce redundancy, and enhance the representativeness of classification information. The dataset was then divided into a training set (60%) and a test set (40%) using stratified sampling. SVM excels in soil spectral classification due to its advantages in handling small-sample, high-dimensional, and nonlinear data.

The spectral characteristics of this laterite profile indicate that in the visible range, spectral reflectance decreases with increasing organic matter content, while overall reflectance gradually increases from the surface to deeper layers. An absorption feature around 850 nm reflects the high iron content in the profile. The above characteristics align with the soil-forming pattern of strong weathering and enrichment of iron-aluminum oxides in laterite under high-temperature and high-rainfall conditions.

Principal Component Analysis of the soil profile revealed that PC1 (accounting for 90% of the information) exhibits significant variation along the depth gradient, shifting from positive to negative values with increasing depth. PC2 (accounting for 9% of the information) shows minimal variation, fluctuating around zero. The first two principal components reflect the changes in attributes of each genetic horizon with depth.

Model validation results show that under 100 random samplings, the average accuracy reached 0.869, with most sampling accuracies concentrated around 0.9. With the optimal parameter combination, the model validation accuracy achieved 1, demonstrating the effectiveness of point-based hyperspectral data combined with machine learning algorithms. This method provides an efficient and non-destructive field solution for soil profile identification and classification, significantly enhancing the efficiency and accuracy of soil surveys.

Fig.1 Spectral Curve of Soil Profile Horizons

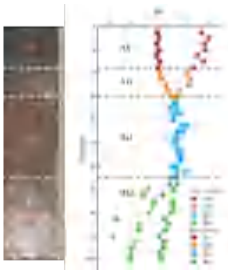


Fig.2 Plot of Principal Component Analysis (PCA) Scores vs. Depth in a Soil Profile

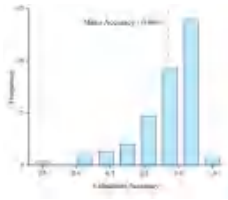


Fig.3 Frequency Distribution of Validation Set Accuracy (100 Random Samples)

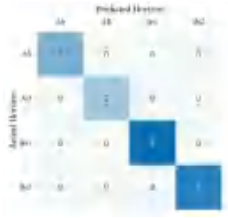


Fig.4 Confusion Matrix for Soil Horizon Classification Results

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# Estimation of soil inorganic carbon storage for profiles based on spectroscopy

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**ABSTRACT**

Recent studies have demonstrated that the SIC stock (SICs) in the top 0-2 m of soil is comparable to the SOC stock (SOCs). SIC mainly exists in the form of calcium carbonate ($CaCO_3$) and influences soil buffering capacity and the availability of various nutrient elements.

In recent years, spectroscopic techniques have shown potential in the detection and quantification of SIC, particularly $CaCO_3$. However, existing studies have primarily focused on surface soil or discrete point samples, which cannot accurately reflect the continuous variation of $CaCO_3$ content or density with depth and the SICs.

The profiles were collected from the coastal plain of Dongtai, Sheyang, Tongzhou, and Cixi. In each profile, strip samples and bulk density samples were collected at 10 depth intervals: 0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-50, 50-60, 60-80, and 80-100 cm. The $CaCO_3$ content was determinated by gas volume method and SICDicm was calculated using equation (1). The subsequent process of spectral data determination, preprocessing, calibration, and validation is shown in Fig. 1.

$$SICD_{icm}=SIC_i\times BD_i\times A\times(1-C_i)\div 10 \quad (1)$$

where, the letter A represents one centimeter.

The descriptive statistics for properties of calibration and validation sets were shown in Table 1. A strong linear relationship was found between measured SIC and SICDicm (Fig. 2). Therefore, it can be inferred that soil reflectance spectra should also be able to estimate SICDicm based on this linear relationship.

Results indicate excellent PLSR models were established, which can estimate SIC and SICDicm (Table 2 and Table 3). The SICDicm_40pre values estimated using the PLSR model were converted to SICDi_10pre and SICspre. The scatterplot indicates that the estimated results for SICDicm were very close to the determined values.

We can conclude that the strong linear relationship between SIC and SICDicm is the mechanism of SICDicm estimation using spectroscopy. Using continuously collected reflectance spectra along the profile allows both the mapping of the vertical SIC distribution and the estimation of SICs for the soil profile.



Fig.1 Steps for estimation and validation for SICs and SICDicm using spectroscopy Fig.2 Scatterplot for SIC_10 and SICDicm_10

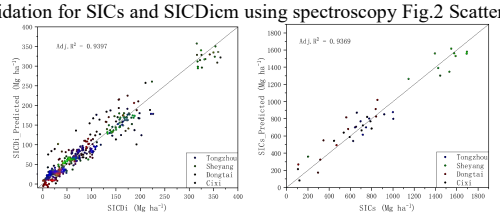


Fig.3 Scatterplot for SICDi_10 and SICDi_10pre Fig.4 Scatterplot for SICs_10 and SICs_10pre

Table 1 Descriptive statistics for soil properties

| Variable | Calibration set (10 profiles, 100 samples) | | | | | Validation set (2 profiles, 20 samples) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | SD | CV | Min | Max | Mean | SD | CV |
| BD | 1.075 | 1.505 | 1.435 | 0.125 | 0.08 | 1.365 | 1.505 | 1.455 | 0.050 | 0.03 |
| SIC | 12.530 | 2.00 | 5.188 | 4.250 | 0.59 | 11.540 | 2.450 | 4.990 | 2.957 | 0.60 |
| SICDicm | 19.815 | 0.250 | 7.867 | 6.970 | 0.82 | 17.668 | 0.306 | 6.374 | 6.441 | 0.65 |
| SICs | Calibration set (50 profiles) | | | | | Validation set (2 profiles) | | | | |
| | 1469.13 | 110.93 | 819.35 | 445.27 | 0.54 | 1698.71 | 108.97 | 824.00 | 470.13 | 0.57 |
| | 8 | 3 | 5 | 5 | 6 | 0 | 8 | 0 | 2 | 1 |

Table 2 The calibration and validation results for Spec_10 and SIC_10

| | Calibration (n=500) | | | | Validation (n=120) | | |
|---|---|---|---|---|---|---|---|
| PC number | RMSEc | $R^2_c$ | RMSEcv | $R^2_{cv}$ | RMSEp | $R^2_p$ | RPIQ |
| 6 | 0.872 | 0.900 | 10.605 | 0.586 | 10.542 | 0.857 | 2.612 |

Table 3 The calibration and validation results for Spec_10 and SICDicm_10

| | Calibration (n=500) | | | | Validation (n=120) | | |
|---|---|---|---|---|---|---|---|
| PC number | RMSEc | $R^2_c$ | RMSEcv | $R^2_{cv}$ | RMSEp | $R^2_p$ | RPIQ |
| 8 | 1.585 | 0.848 | 1.695 | 0.880 | 1.755 | 0.843 | 2.736 |

**Acknowledgments**

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# Effect of spectral range, spectral pre-processing, calibration method, and sample classification on soil property predictions using a country-scale soil spectral library for Hungary

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## ABSTRACT

Spectroscopy, particularly when integrated with conventional laboratory analyses, offers a rapid, non-destructive, and cost-effective approach for assessing soil properties. However, the accuracy of spectroscopic predictions depends on multiple factors, including the spectral region, pre-processing techniques, calibration models, and the method of sample grouping. In this study, we evaluated the predictive performance of a national-scale soil spectral library for Hungary by systematically testing how these factors influence the accuracy of soil property predictions, to identify optimal modeling strategies for large-scale applications.

The soil spectral library used in this study was developed within the framework of the Agrotechnology National Laboratory project. It is based on archived soil samples originally collected in 1992 as part of the Hungarian Soil Information and Monitoring System. These samples represent genetic soil horizons from 1236 geoReferencesd monitoring sites across Hungary and had previously been analysed for key physical and chemical properties. The References parameters used in this study included organic carbon, bulk density, particle size fractions (clay, silt, sand), pH, calcium carbonate, exchangeable bases (Ca, Mg, K, Na), exchangeable acidity, soluble salts, electrical conductivity, cation exchange capacity, and base saturation.

Spectral measurements were performed using two complementary instruments: ASD LabSpec 4 Hi-Res spectrometer for the visible and near-infrared (VNIR), and a Bruker Alpha II FTIR spectrometer for the middle-infrared (MIR) range.

To evaluate the predictive performance of soil spectroscopy under different modeling configurations, three algorithms were employed: Partial Least Squares Regression, Random Forest, and Cubist. Spectral data were used in three configurations - VNIR, MIR, and combined VNIR-MIR - and subjected to a range of pre-processing techniques, including raw spectra, moving average smoothing, Savitzky–Golay filtering, and first derivative transformations. All possible combinations of spectral type, pre-processing method, and calibration model were tested systematically.

To investigate how sample grouping affects model performance, the dataset was segmented into several categories according to various classification schemes. These included groupings based on parent material, main soil type (Hungarian classification), WRB References soil groups, textural class, county, elevation class, land cover, and unsupervised k-means clustering, in addition to the full dataset (no segmentation).

This paper presents the outcomes of this comprehensive modeling framework, highlighting how different spectral configurations, pre-processing techniques, calibration methods, and sample segmentation strategies influence the accuracy of soil property predictions across a national-scale spectral library.

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# Layer–Profile Integration for Numerical Soil Classification

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**ABSTRACT**

Numerical soil classification offers a scalable and objective alternative to traditional horizon-based systems, which depend on expert interpretation and are often challenging to apply consistently across complex and heterogeneous landscapes. In Australia, where soils exhibit pronounced spatial and vertical variability, numerical classification enables reproducible mapping based on measured or modelled soil properties.

Building on previous work that defined soil profile classes through clustering of soil properties across depth intervals, this study proposes a new framework to explicitly link profile classes with their constituent layer classes at the pixel level. The classification is based on a suite of relevant soil properties—available water capacity, bulk density, cation exchange capacity (CEC), effective CEC, pH (in both water and calcium chloride), organic carbon content, and soil texture (sand, silt, and clay percentages). The approach captures the vertical structure of soils by associating each profile class with the sequence of layer classes occurring across five standard depth intervals (0–5, 5–15, 15–30, 30–60, and 60–100 cm). By integrating depth-specific layer class maps with the profile class map at 90 m resolution across Australia, the framework will produce a national-scale, pixel-level composition table describing layer sequences within each profile. This linkage provides a means to quantify internal variability within profile classes and enhance the interpretability of classification outcomes.

This proposed framework has the potential to strengthen numerical soil classification by addressing inconsistencies in vertical composition and improving the functional relevance of soil maps. It establishes a foundation for assessing classification reliability, detecting horizon transitions, and analysing spatial patterns in soil organisation across diverse Australian landscapes.

**Keywords:** numerical soil classification; soil profile classes; layer classes

**Acknowledgments**

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# Harmonization of Soil Typological Units Across Administrative Regions: A Case Study from Italy

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**ABSTRACT**

A digitized soil map, accompanied by an associated and harmonized database, is crucial to support land management policies at the national level. Currently, the 1:250,000 scale soil map of Italy is complete, but it appears as a heterogeneous mosaic. Harmonizing cartographic units that are disjointed across different administrative areas, along with the inclusion of new soil profiles to increase detail, constitutes a complex and time and labor-intensive task (Fig1). The objective of this study is to test a semi-automatic numerical classification process to correlate the Soil Typological Subunits (STS) of the Coastal Soil Region 60.7, located between Tuscany and Lazio. The References database includes 1200 soil profiles, organized into 187 STS, representing 19 different References Soil Groups (RSG) according to the WRB 2022 classification system.

The profile comparison integrates both horizon-level and site-level attributes, including continuous properties and categorical variables. The analysis was conducted in R using the aqp v.2.1 package (Algorithms for Quantitative Pedology). The workflow involved creating a SoilProfileCollection object, deriving the distance matrix, and using it as the basis for clustering.

The innovative aspect lies in the handling of ordinal data, allowing a quantitative treatment of qualitative variables (e.g., horizon names, drainage classes), and in the integration of RSG taxonomic distances. Preliminary results, evaluated with statistical indices such as cophenetic correlation, indicate that the DIANA (Divisive Analysis) clustering algorithm performs very well on datasets containing between a few dozen (≈50) and several hundred (≈500) profiles.

Finally, the positioning of soil profiles via nMDS plots (non-Metric Multidimensional Scaling), following the clustering, proved to be an objective method for: (i) the semi-automatic assignment of new profiles to existing STS, and (ii) assessing the proximity between STS along the border between Lazio and Tuscany. (iii) The fully automated reassignment of profiles to clusters, however, differs significantly from the results reported in the regional soil-type catalogues, more so when many variables are considered.




Fig1 *Diagram that illustrates soil correlation is a continuous process, not a single event.*

# Transformation of Aluminum Forms During Andosol Genesis in Japan

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**ABSTRACT**

Significant changes in the chemical forms of aluminum (Al) occur during the formation of Andosols. Based on data published in the literature, the author reviewed the changes in Al speciation during the pedogenesis of Andosols under warm and humid climates. In the parent material, volcanic ash, Al exists in tetrahedral form, and it initially undergoes a transformation to octahedral form in the early stages of weathering. At this stage, the octahedral Al forms amorphous materials, which later become constituents of poorly crystalline aluminosilicate minerals, primarily allophane and imogolite (collectively referred to as allophanic materials). The formation of allophanic materials would require ca. 1 k years or more. Andosols with high contents of allophanic materials correspond to Allophanic Andosols, whereas earlier-stage Andosols correspond to Vitric Andosols. Allophanic materials are metastable and cannot maintain their structure under strong acidification, as they dissolve. Consequently, under humid conditions, the disappearance of allophanic materials occurs in the strongly acidified surface horizon, and the octahedral Al in allophanic materials is converted into Al-humus complexes. Some dissolved Al becomes exchangeable Al, which strongly inhibits plant growth. At this stage, the soils correspond to Non-allophanic Andosols. In Japan, Andosols derived from volcanic ash erupted during the Holocene (ca. 12 k years ago to the present) generally correspond to Vitric or Allophanic Andosols, whereas those derived from older volcanic ash correspond to Non-allophanic Andosols. Even in Non-allophanic Andosols, the subsoil receives less acid from precipitation or plants, resulting in weaker acidification compared to the surface horizon; therefore, the content of allophanic materials is considered higher in the subsoils. This explains the actual morphological features of Andosol profiles well. With further weathering, Al would become a constituent of more crystalline and thermodynamically stable minerals such as gibbsite and halloysite, and the soils cease to be Andosols. Thus, focusing on Al provides a better understanding of the formation and profile morphology of Andosols under warm and humid climates.

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# Efforts to develop modern objective numerical data sources to support universal approaches of soil classification

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**ABSTRACT**

Most soil classification systems developed before computers and computer supported decision methods became available. Activities based on earlier and current international and national systems resulted in huge amount of data. The diversity of different survey, laboratory and classification methods make difficult to produce harmonized, quantitative data and mapping frameworks.

Pedometric approaches (centroid methods, distance calculations) proved to be useful to asses pedodiversity. The paper will summarize and exemplify some of those efforts.

The second part of the presentation will discuss the possibility to apply new objective data sources, such as remote and proxy-sensing technologies to support the understanding of existing and unknown relationships. Examples of applications of conventional laboratory and spectral data-based evaluations of soil similarities and differences will be presented.

# Water-Microbe-Mediated Rhizosphere Microbial Communities Reshaping Agroecosystem Resilience

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**ABSTRACT**

The agricultural 'Green Revolution' has substantially mitigated global food scarcity; however, over-reliance on chemical inputs—including fertilizers and pesticides—has triggered severe soil degradation and widespread environmental pollution, which exacerbates agroecosystem vulnerability against the pressure of climate change. This study identifies water-microbe-mediated rhizosphere microbial communities (SynComs) as the core mechanism for reshaping agroecosystem resilience, with improving soil health as the pivotal entry point for the transition from conventional intensive farming to low-carbon green agriculture. We propose three quantitative breakthroughs for this transition: a 30% reduction in chemical fertilizer and pesticide use, a 20-50% increase in water- and nutrient-use efficiencies, and a 10-30% increase in water-to-carbon biotransformation in rainfed dryland ecosystems. As soil water-microbe-mediated rhizosphere microbial communities are the key factors for this transition, we construct a systemic framework, encompassing the design of climate-smart SynComs, exploration of biophysical pathways for water-to-carbon biotransformation, development of bio-based nitrogen fixation, and exploitation of water-sensed bio-enhancers, all oriented to the triple strategic goals of safeguarding food security, maintaining soil health, and cutting greenhouse gas emissions. Leveraging water-microbe-mediated rhizosphere microbial communities, we establish a pipeline for novel SynComs via high-throughput isolation of functional microorganisms, single-cell Raman-based sorting of active microbial strains, and precise assembly of functional microbiomes. Large-scale field trials under Zhejiang Province's agricultural science and technology program validate the efficacy of this water-microbe-mediated SynComs. The bio-enhancers increased rice yields by 16.6–17.8%, while nitrogen-fixing biofertilizers effectively enhance soil health. These findings reveal that water-microbe-mediated rhizosphere SynComs serve as the core ecological engine governing material and energy cycling in agroecosystems, and that soil microhabitat regulation constitutes an effective pathway for the sustainable transformation of global agriculture. Delivering pivotal scientific insights into the restoration of soil health, the governance of food security, and national dual-carbon strategic objectives, SynComs fortify the agroecosystem resilience amid the context of anthropogenically driven climate change and its cascading ecological impacts.

# Confronting Water Availability versus Water Accessibility in Plant–Soil Relations

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**ABSTRACT**

Water availability has long been a key parameter in hydrology, agronomy, and plant physiology, but recent advances highlight the necessity of distinguishing it from water accessibility – the fraction of soil water that plants can actually extract for physiological functions. Water availability is traditionally quantified as the difference between field capacity and the permanent wilting point, yet this metric does not account for soil structure, root system architecture, and dynamic soil–plant interactions that influence how much water is actually accessible to vegetation. This report synthesizes recent findings on the physical and biological controls of water accessibility, explores its implications for ecohydrology and climate resilience, and discusses how next-generation models can better integrate accessibility to improve predictions of drought stress, ecosystem water use efficiency, and land–atmosphere feedbacks. Recognizing the role of water accessibility in plant–soil relations provides a more nuanced understanding of drought impacts, crop water use, and the hydrological cycle under a changing climate.

# Physically informed Bayesian mixing models reveal more realistic root water uptake profile

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**ABSTRACT**

Root water uptake is critical for plant water relations and ecosystem functioning, yet accurately quantifying depth-specific root water uptake profiles remain challenging due to limited isotopic constraints and underdetermined mixing solutions. Here, we introduce CrisPy-Physical, an isotope-based Bayesian mixing model that integrates a physically based root water uptake process into a continuous nonparametric estimation framework. Virtual tests demonstrated that CrisPy-Physical substantially reduced errors and uncertainties of estimated root water uptake profiles by 90% and 60% than the previously developed CrisPy (with no physical constraints), respectively. Notably, CrisPy-Physical successfully reproduced hydraulic redistribution patterns, which CrisPy failed to capture. Field tests in a vegetated lysimeter showed that both CrisPy and CrisPy-Physical captured the drought-induced shift of root water uptake towards deeper soil layers and its subsequent reallocation to shallow layers after rainfall. However, CrisPy barely captures root water uptake below 1.5 m, contradicting physiological expectations supported by fine-root profiles and water potentials between leaf and soil. Overall, CrisPy-Physical not only offers a robust and physically consistent framework for inferring root water uptake profiles, but also advances our mechanistic understanding of plant water use strategies under various climate conditions.

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# Soil-Water and Groundwater: Connections at the Food-Water-Energy Nexus

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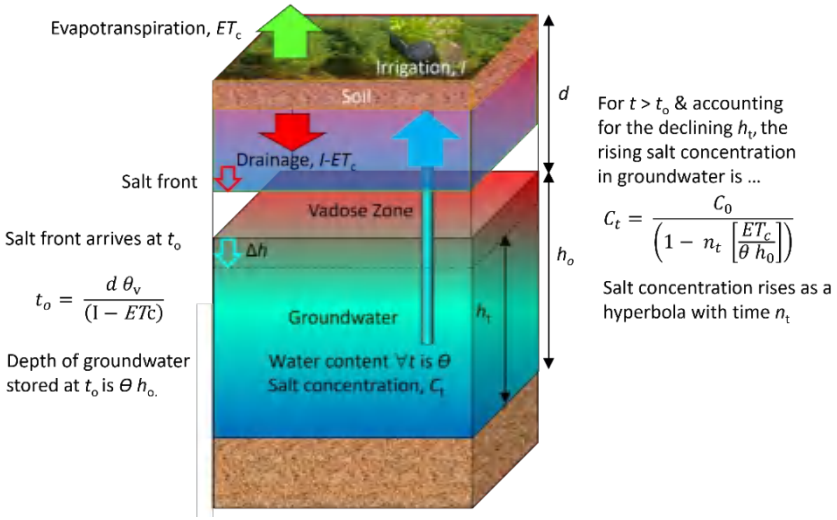
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## ABSTRACT

Globally there are critical opportunities and profound challenges at the food-water-energy nexus. Crucial to the nexus is the role of soil-water and groundwater. Soil-water is needed to produce food. Groundwaters provide 99% of the world's useable freshwater supplies. Agriculture consumes 70% of the world's freshwater. From the 2010 baseline there is projected to be 56% gap in food production by 2050. Irrigation is required for much of the world's food production, as 40% of the food grown globally uses irrigation. Yet some 10% of today's irrigation water is "stolen" from tomorrow, as it relies on today's use of non-renewable groundwater to produce food. It has recently been suggested that with "business-as-usual", we will reach "peak groundwater" around 2050.

Groundwater-protection measures are needed for agricultural production of food, fibre, and fuel in the deserts of the United Arab Emirates (UAE). Our work in the UAE① focussed on groundwater protection under the production of the halophyte *Salicornia* growing in a sandy soil using irrigation with the reject brine from a desalination unit. Energy is used to desalinate the brackish groundwater in desert realms. The freshened water can be used to irrigate high-value crops with low salinity tolerance such as vegetables or dates. With irrigation of halophyte using the reject brine from desalination units, a leaching-fraction is needed to despatch the residual salts out of the rootzone back to groundwater. Heuristic modelling predicts a hyperbolic rise in groundwater salinity.




Solutions to extend groundwater life could involve using zero-liquid-discharge desalination, or the conjunctive use of alternative waters, either directly as an irrigation, or indirectly via blending or managed aquifer recharge. There are environmental opportunities and challenges at the nexus. Sustainable solutions will rely on innovations and stakeholder discussions to assess benefits, synergies, trade-offs, and the impacts of various options.

**Acknowledgments**

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# A Complex-Plane Representation of Gas Diffusivity in Variably Saturated and Fractured Porous Media

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## ABSTRACT

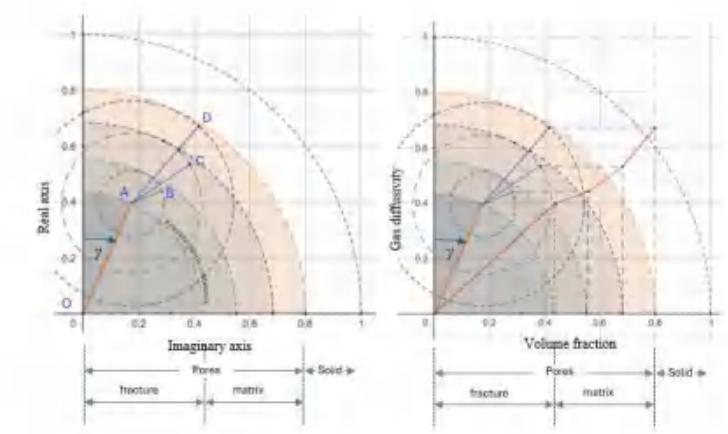
Knowledge of gas diffusivity ($D_p/D_o$, where $D_p$ and $D_o$ are gas diffusion coefficients in soil and in free air, respectively) and its relationship to moisture is as essential prerequisite for quantifying soil–atmosphere interactions in both natural and engineered porous systems. Traditional power-law expressions for predicting $D_p/D_o$ largely rely on empirical parameters that obscure the directional complexity of pore networks, particularly under variable saturation and structural anisotropy.

In this study, we present a unified complex-plane framework that represents gas diffusivity as a vector-derived quantity to represent variably saturated media and fracture-matrix systems. The framework introduces a dual impedance concept, where air-phase availability defines the impedance magnitude, and directional changes in diffusive flow appear as a phase shift on an Argand plane. This approach captures the evolving geometry and directionality of gas transport as soils transition from dry to wet states or from fracture- to matrix-dominated domains.

Using new and published $D_p/D_o$ data, we demonstrate how the effective impedance angle evolves with changing water content and structural orientation. For variably saturated media, increasing moisture rotates the principal diffusion axis, reflecting a transition from freely connected air pathways to moisture-constrained pore connectivity. For fractured media, the framework generalizes single and multiple fractures of varying orientations by mapping fracture porosity and alignment as angular components in the complex plane. Fractures impose a baseline anisotropy, while matrix pores contribute an omnidirectional component as water drainage progresses, producing distinct diffusivity trajectories in the complex domain.

Application to fractured limestone revealed a transition from a fracture-controlled regime (mean impedance angle ≈58°), through an interactive fracture–matrix regime (≈85°), to a matrix-controlled regime (≈65°), consistent with evolving hydraulic connectivity. This complex-plane representation provides a mechanistically meaningful approach to describe moisture-induced rotation of the principal diffusion axis in variably saturated soils, enabling improved characterization of soil aeration, $CO_2$ flux, vapor transport, while capturing preferential gas flow and fracture–matrix exchange dynamics in fractured media.

The accompanying figure illustrates the complex-plane representation of fracture–matrix duality and the corresponding trajectories of soil-gas diffusivity across the two domains.



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# Modeling Water Movement in Gravity Potential Difference Irrigation Based on Hydraulic Potential Difference-Driven Outflow Mechanism

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## ABSTRACT

Gravity potential difference irrigation (GPDI) systems maintain a stable water level within the irrigator, leveraging the combined effects of soil matrix potential and gravity potential to continuously supply water to the crop root zone based on plant water demand. This study investigated the soil water infiltration characteristics under GPDI and the factors affecting them. Nine scenarios of irrigator opening adjustments were designed: experimental irrigator openings were set at 6 cm, 2 cm, and 1 cm, while the filling thickness of the capillary soil layer within the irrigator were set at 9 cm, 6 cm, and 3 cm, respectively. Wetting patterns were analyzed using image processing. The discharge of GPDI and the moisture distribution within the wetting patterns were also analyzed. Furthermore, based on the hydraulic potential difference-driven outflow mechanism, a soil water movement model for GPDI was developed using HYDRUS-2D software. The accuracy of the model was validated with measured data from indoor experiments. Simulation results under different scenarios indicated that moisture primarily concentrated near the irrigator under GPDI. Adjusting the irrigator opening and the thickness of the capillary soil layer significantly affected the irrigator's discharge rate, moisture distribution, and wetting morphology. Specifically, larger irrigator openings and thinner capillary soil layers resulted in larger wetting areas and faster wetting front advancement, with higher soil saturation near the irrigator outlet. However, in scenarios with a 1 cm irrigator opening and a 9 cm capillary soil layer, the soil was less likely to reach saturation. The burial depth of the irrigator significantly influenced the position of the wetted body and the time for the wetting front to reach the upper and lower boundaries. Yet, before the wetting front reached the boundaries, its impact on GPDI outflow and wetting front advancement rate was not significant. This study provides a scientific References for the design optimization, management, and further promotion of GPDI technology

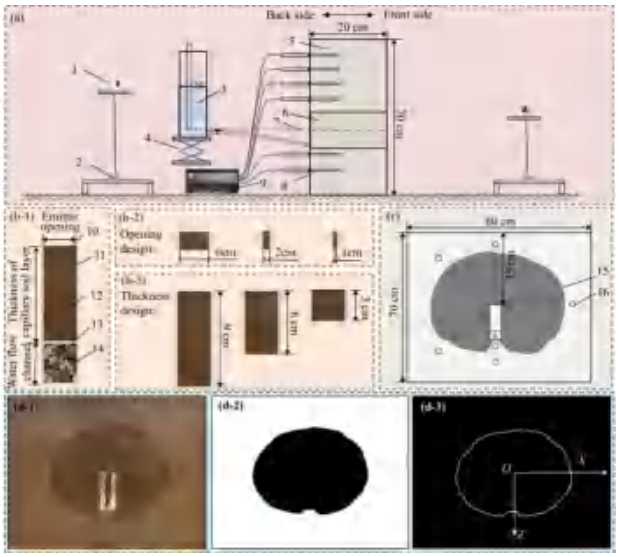


Fig. 1 Diagrammatic sketch of gravitational potential difference system and wetting body image processing (a) Gravitational potential difference experience device,（b-1）Design drawing of the irrigation emitter；（b-2）Design of emitter opening for irrigation emitters;（b-3）Design of capillary soil layer thickness for irrigation emitters；(c) Diagrammatic sketch of wetting front; (d-1) Captured image of wetting body, (d-2) Binary segmentation of wetting body; (d-3) Morphological image and Cartesian coordinate system position of wetting body. 1-Camera,2-Sliding rod,3-Mariotte bottle,4-Subsurface irrigation water level stabilization device,5-Soil box,6-Gravitational potential difference irrigator,7-Designed subsurface irrigation saturated water table line,8-PICO probe,9-Soil moisture data logger,10.Emitter opening,11-Impermeable outer wall of irrigator (2cm thickness),12-Capillary soil layer,13-Geotextile-soil-water interface,14-Water flow channel,15-Wetting body,16-TDR measurement hole

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# Impact of Biosolids on Plant Available Water and Beyond

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**ABSTRACT**

The use of biosolids in agricultural practices is prevalent to enhance soil fertility and water retention. Biosolids are rich in nutrients and organic matter; thus, land-application of biosolids contributes to circular economy principles. However, biosolids also contain contaminants, such as microplastics, which can lead to pollution of soils and deterioration of soil functions. Long-term biosolids application significantly improved soil chemical and physical properties, with organic matter increasing by up to 71%, bulk density decreasing by 22%, and field capacity increasing by 24%; however, biosolids application also led to a decrease of pH from 5.5 to 4.8. Enhanced pore connectivity revealed by X-ray computed tomography provides microscale explanation for improved water retention. While biosolids applications increased soil organic matter and microplastic concentrations in the soil, correlation analysis revealed a negative relationship between organic carbon and extractable microplastics when controlling for biosolids application dose. In addition, soil physical parameters were more strongly correlated with organic matter than with microplastics concentrations, suggesting that the impacts of organic matter dominates over microplastics. Our findings demonstrate that benefits of biosolids outweigh quantifiable short to medium-term risks from associated microplastics, though long-term monitoring remains essential.

# Root zone in the Earth system

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**ABSTRACT**

The root zone is a vital part of the Earth system and a key element in hydrology, ecology, agronomy, and land surface processes. However, its definition varies across disciplines, creating barriers to interdisciplinary understanding. Moreover, characterizing the root zone is challenging due to a lack of consensus on definition, estimation methods, and their merits and limitations. This paper provides a holistic definition of the root zone from a hydrology perspective, including its moisture storage, deficit, and storage capacity. We demonstrate that the root zone plays a critical role in the biosphere, pedosphere, rhizosphere, lithosphere, atmosphere, and cryosphere of the Earth system. We underscore the limitations of the traditional reductionist approach in modeling this complex and dynamic zone and advocate for a shift towards a holistic, ecosystem-centered approach. We argue that a holistic approach offers a more systematic, simple, dynamic, scalable, and observable way to describing and predicting the role of the root zone in Earth system science.

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# Predawn Leaf Water Potential of Grapevines Is Not Necessarily a Good Proxy for Soil Moisture

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**ABSTRACT**

In plant water relations research, predawn leaf water potential (Ψpd) is often used as a proxy for soil water potential (Ψsoil), without testing the underlying assumptions that nighttime transpiration is negligible and that enough time has passed for a hydrostatic equilibrium to be established. The goal of this research was to test the assumption Ψpd = Ψsoil for field-grown grapevines. A field trial was conducted with 30 different cultivars of wine grapes grown in a single vineyard in arid southeastern Washington, USA, for two years. The Ψpd and the volumetric soil water content (θv) under each sampled plant were measured multiple times during several dry-down cycles. The results show that in wet soil (Ψsoil > −0.14 MPa), Ψpd was significantly lower than Ψsoil for all 30 cultivars. Under dry soil conditions (Ψsoil < −0.14 MPa) Ψpd lined up better with Ψsoil. These results suggest that for wet soils Ψpd of grapevines cannot be used as a proxy for Ψsoil, while the Ψpd = Ψsoil assumption may hold for dry soils.

# Water Balance and Plant Available Soil Water: Linking Soil Physics and Hydrology

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**ABSTRACT**

The water balance, referred to by Robert Horton as the "central problem of hydrology," and plant available soil water are closely, though imprecisely, linked. Predicting the water balance requires prediction, as a function of climate variables (precipitation and potential evapotranspiration), of the fraction of the precipitation used by vegetation. Contrastingly, plant available soil water is considered to be the water "held in soil that is accessible for plant roots to absorb after excess water drains," bounded by the permanent wilting point." Such a description is not clearly enough defined to enable scientific tests of prediction by measurement and implies furthermore a temporal distinction (at some times water is draining from the soil, while at others, water is being used by the plants) which clearly does not exist. However, the amount of water actually used by plants can be measured and predicted. Of late, the hydrology community has been gravitating to the perspective that it is not primarily the physical properties of the soil that control the behavior of the plants, but the adaptation of vegetation and the living soil to the climate system that control soil development, plant growth, and the physical properties of the soil.

In our perspective, the plant use of precipitation, i.e., actual evapotranspiration (not precisely water held in the soil) and the water that is left over to form soil, i.e., run-off, can only be understood if one establishes first what the dependence of plant growth is on evapotranspiration, and of soil depth on run-off. Only then, can one find an optimal partitioning of P into Q and ET which maximizes plant and microbial productivity. Thus, the point of view that plants determine the water content of the soil, rather than that the water content of the soil controls plant growth, can form the basis of a successful theory of the water balance, vegetation growth, and productivity, even if it is not the entire picture. The benefits of this change in perspective are large: 1) Predictive capability of streamflow response to climate change, including climate and basin size dependence of elasticity and storage fluctuations, 2) associated predictive treatments of moisture recycling and scale dependence of ET, 3) Predictive capability of the variability of net primary productivity across biomes and climates, 4) Predictive capability of tree species richness, 5) Verified predictions of continental scale ET, 6) Understanding the current latitudinal dependence of vegetational optimality temperatures and the Phanerozoic global temperature record.

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# A Process-Based Proxy for the Water Availability to Plants

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**ABSTRACT**

Total plant available water (TAW) is traditionally defined as the difference between field capacity (FC) and wilting point (WP). The portion of TAW between FC and the limiting point (LP) supports potential transpiration without drought stress and is referred to as readily available water (RAW). However, using FC as the upper limit of both TAW and RAW is questionable (De Jong Van Lier, 2017; Logsdon, 2019). Plants can continue transpiring at rates above FC, meaning that water beyond the traditional TAW range is effectively available. This additional water depends on soil hydraulic properties (SHP) and rainfall and crop characteristics, so an equivalent water content defining the upper limit of TAW and RAW must reflect both SHP, climate and crop. This revised concept will be discussed.

The lower TAW limit (WP) is commonly assigned to a matric potential of hWP = 1,500 kPa. Because most soils show a very small derivative dθ/dh at such high suction, WP is relatively insensitive to the exact value of hWP. By contrast, there is no widely accepted matric potential for the lower limit of RAW (LP). In the range where LP is typically located, dθ/dh is larger, making LP more sensitive to definition. Empirical approaches define LP based on FC, WP, atmospheric demand, and crop sensitivity (Raes et al., 2009) or as matric potential thresholds tied to crop type and evaporative demand (Feddes et al., 1978). These proxies, however, do not account for unsaturated hydraulic conductivity, a key determinant in process-based root water uptake (RWU) models (De Jong Van Lier et al., 2013). A new framework for LP and WP using process-based RWU models and the matric flux potential (the integral of hydraulic conductivity) will be presented.

Flux-based TAW and RAW derived from these dynamic limits will be compared with traditional estimates for a diverse soil set, and their relationships with crop behavior and soil water balance components will be discussed.

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# Defining, monitoring, and utilizing plant available water information as a public good

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**ABSTRACT**

Plant available water (PAW) is a misunderstood and underappreciated global water resource, and there is tremendous potential for improved PAW monitoring to provide diverse societal benefits. Unlocking that potential requires, first, a correction of the widely accepted but inaccurate way in which the upper limit of PAW, i.e. field capacity, has been estimated for almost a century. Estimating field capacity as the volumetric water content of the soil at a matric potential of -33 kPa consistently underestimates field capacity by ~20%, leading to significant underestimates of PAW. Better field capacity estimates are possible by interpreting data from in situ soil moisture sensors or by using matric potential thresholds of -10 kPa or even -7.5 kPa. Using a matric potential of −33 kPa as a threshold to represent field capacity is not scientifically justified and should be discontinued. Adopting better field capacity estimates opens the door to developing beneficial PAW monitoring systems at socially relevant scales. One such system is the Oklahoma Mesonet, which includes one of the world's longest running soil moisture monitoring networks. This system provides automated daily statewide PAW observations for three depths, which are routinely used by the public. Those data are also converted to fraction of available water capacity (FAW) values, such that FAW = 1 corresponds to field capacity and FAW = 0 corresponds to permanent wilting point. These FAW values can be used for the public good through improved wildfire danger forecasting, better drought monitoring, more effective targeting of drought relief payments, and more. As researchers and stakeholders continue to unlock these benefits, we may move closer to a day when knowing current PAW levels will be as commonplace as knowing today's air temperature or rainfall amount.

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# Development of soil mechanical stability during initial soil formation – from field to rhizosphere scale

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**ABSTRACT**

Pre-consolidation stress is a measure of mechanical stability on the bulk soil scale while aggregate stability and penetration resistance measurements can be used to assess soil strength at the micro/root scale. Starting from initial soil deposition soil stability is expected to develop over time by processes like consolidation, shrinking-swelling, root reinforcement or exudation of mucilage by roots. We studied the development of soil stability over a cropping period from 2019-2024 in Bad Lauchstädt (Germany) where excavated plots were refilled with homogenized loam and sand and planted with two contrasting maize (*Zea mays*, L.) genotypes. On the field scale loam plots showed a distinct increase of pre-consolidation stress for the first three years while sand plots did not display any temporal pattern (Rosskopf et al. 2022a). In a second laboratory study employing the same homogenised substrates we investigated the combined effect of mucilage concentration and soil water content on penetration resistance PR (Rosskopf et al. 2022b). A stainless-steel cone resembling the maize root geometry was mounted on a high-precision material testing device and pushed through the remoulded soil samples to simulate root growth. Loam and sand were mixed with chia (*Salvia hispanica,* L.) seed mucilage at various concentrations and samples were adjusted to a range of water contents. Higher mucilage concentrations significantly lowered PR in the driest loam, thus reducing the energy cost of plant root growth whereas in moister conditions it had the opposite effect. In a third study we investigated the direct effect of root growth on local soil deformation in the rhizosphere using X-ray mCT measurements and digital image correlation (Rosskopf et al. 2025). We could show that the extent of the deformation zone depended on soil texture and genotype. Our results provide valuable information on soil stabilisation processes during initial soil formation and highlight the complex interaction of physical and biological stabilisation mechanisms on various scales.

**Acknowledgments**

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# Rhizosphere Hydraulic Regulation Across Soil Textures: Evidence for Texture-Dependent Mucilage Function

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**ABSTRACT**

Plants actively modify the physical and chemical properties of the rhizosphere to overcome water and nutrient limitations. Root mucilage is increasingly recognized as a central regulator of rhizosphere hydraulic properties, yet quantitative evidence for how its function varies across soil textures and moisture regimes remains limited.

We combined a series of complementary experiments to address this gap. First, we used a simplified rhizosphere model to examine how varying concentrations of mucilage extracted from maize seedlings alter soil water retention, unsaturated hydraulic conductivity, and solute diffusion in sand, sandy loam, and loam across different moisture levels. In parallel, we conducted a $^{14}C$ pulse-labelling experiment together with neutron radiography to quantify how plants regulate belowground carbon allocation, specifically root exudation, under contrasting soil texture and moisture conditions, and how this carbon investment feeds back on rhizosphere hydraulic properties.

The rhizosphere model revealed pronounced texture-dependent mucilage effects. Coarse-textured soils required higher mucilage concentrations to increase water-holding capacity, whereas even low mucilage levels enhanced retention in finer soils. In sandy soils, mucilage reduced Ca diffusion by increasing liquid-phase viscosity across moisture levels. In contrast, in fine-textured soils, mucilage prevented the sharp decline in diffusion during drying, indicating improved liquid connectivity.

Neutron radiography of 6-week-old maize plants showed consistently wetter rhizosphere zones compared to bulk soil, with the strongest moisture gradients in sandy soils, evidence of enhanced mucilage-mediated hydration where hydraulic continuity is naturally low. The $^{14}C$ pulse-labelling experiment further demonstrated that carbon allocation to the rhizosphere is regulated by soil physical conditions: seminal and lateral roots in sand exhibited higher $^{14}C$ activity than in loam, particularly under dry conditions, and crown roots exuded the most $^{14}C$-labelled carbon in sand–dry soils. Root growth patterns confirmed sustained investment into seminal and lateral roots in sandy soils.

Together, these findings provide converging empirical evidence, from rhizosphere models, neutron imaging, and carbon tracing, that plants exude more, and hydraulically more effective, mucilage in sandy soils. This texture-dependent adjustment enhances water-holding capacity and stabilizes hydraulic continuity where roots would otherwise experience rapid drying. Our results reveal a mechanistic link between soil texture, carbon allocation to exudation, and rhizosphere hydraulic regulation, offering new insights into plant drought responses and informing soil- and crop-specific strategies to improve root-zone water availability.

# Estimating Soil Water Matric Potential from Penetration Resistance Measurements

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**ABSTRACT**

Accurate quantification of soil water matric potential is critical for modeling soil water dynamics and optimizing irrigation management. Direct measurement methods are often limited by narrow operational ranges (e.g., 0 to -85 kPa for tensiometers) and high maintenance requirements. While commercial automated sensors offer improved accuracy and convenience, their cost remains prohibitive for field applications. Here we propose a rapid, cost-effective approach for estimating soil water matric potential (expressed as pF) from penetration resistance (PR) measurements. We conducted controlled laboratory experiments using repacked soil columns with nine soil textures ranging from quartz sand to clay. Tensiomark sensors and a cone penetrometer were used to simultaneously measure pF and PR during soil drying cycles across varying bulk densities (1.1-1.6 g cm-3). Results demonstrated that: (1) both instruments successfully captured dynamic changes in PR and pF across a wide range of soil water contents (pF 0-4.2); (2) pF values exhibited strong logarithmic relationships with PR across all soil types ($R2 > 0.95$); and (3) the regression parameters (slope a and intercept b) of the pF–ln(PR) relationship could be reliably predicted from readily available soil properties including texture class, clay content, and bulk density. Independent validation using separate datasets yielded root mean square errors of 0.14, 0.21, and 0.11 pF units for clay loam, silt loam, and sandy loam soils, respectively. This PR-based approach provides a practical, field-deployable alternative for rapid assessment of soil matric potential, particularly valuable for precision irrigation management and soil hydraulic characterization where cost and ease of measurement are important considerations.

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# A complete morphological and topological description of soil pore structure dynamics during wetting-drying

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**ABSTRACT**

Wetting-drying cycles significantly influence soil structure and are a major driver of its dynamics. Traditional studies employing X-ray tomography have mainly relied on classical scalar descriptors -- such as porosity, bulk density, and pore-size distribution -- to quantify these changes. However, the limited informational capacity of such metrics has recently come under scrutiny. In this work, we advocate for the use of high-information-content vector descriptors: correlation functions (CFs), pore-network models (PNMs), and persistent homology. While CFs and PNMs have already proven effective for investigating soil structural dynamics, the third method -- persistent homology -- remains relatively unexplored in soil science. Its strength lies in capturing subtle topological transformations that may be overlooked by conventional approaches.

We applied these descriptors to quantify and compare structural changes in samples from three horizons of Greyzemic Chernozem (Loamic, Pachic) under different saturation levels throughout a controlled wetting–drying cycle. XCT scanning was performed at 10 saturation points, namely: initial field moisture, pF=0.4 during saturation, full saturation, pF=0.4 during drying and pFs equal to 1.5, 1.8, 2, 4.45, 5.33 and 6.43. A total of 10 XCT scannings for each sample, together with five samples from each of three horizons, resulted in 150 examined 3D images, which then were analyzed. Our analysis provides a quantitative characterization of morphological and topological evolution during cyclic wetting and drying, revealing structural hysteresis and horizon-dependent variations in the degree of structural recovery.

We highlight the primary advantage of high-information-content metrics -- their ability to comprehensively describe soil structure -- while acknowledging their interpretative complexity, as they integrate multiple structural features simultaneously. The proposed methodology offers a robust framework for describing and comparing soil structures across scales and contributes to advancing quantitative soil structural analysis.

A key achievement of this study is the numerical evaluation of soil structural dynamics using descriptors with high information content. Although previous attempts have assessed soil's ability to return to its initial state (elastic hysteresis) they usually relied on low-information-content metrics. In current research, it was possible to estimate hysteresis using distances from three different vector metrics -- a novel approach in soil science. Studying small saturation changes during drying is easier than during wetting, which limited our analysis to a few points: field state vs. pF=1.8, and pF=0.4 during wetting and drying. Soil structure differed at these same saturation points across genetic horizons.

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# A Mechanistic Soil-Plant Model to Assess Soil Water Accessibility

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**ABSTRACT**

The first step in the assessment of soil water accessibility to plants is to define accessibility. One commonly used definition of soil water accessibility is the ratio of the actual water uptake by the root system to the uptake when water is fully accessible and root water uptake is determined by the amount of energy that is available to evaporate water. This definition is applied in soil water balance models that are used for irrigation scheduling, in eco-hydrological models, and in models that simulate land surface-atmosphere, assuming that a tight relationship between soil water accessibility and soil water content in the root zone can be found. This relationship has been investigated in several studies in a 'top-down' approach by observing plant transpiration and root zone soil water content. From these studies, the impact of vegetation, meteorology, and soil on the relationship has been inferred. We raise the question whether we can derive this relationship and assess its tightness using a 'bottom-up' approach that uses basic physical understanding of flow processes in the soil-plant system and that brings together knowledge about root and soil properties across scales ranging from an individual root segment and the rhizosphere around it up to the entire root architecture and the entire soil profile. Using the multiscale modelling approach that we developed, we simulate root water uptake as a function of root system architecture, root segment hydraulic properties (which we can derive from simulations of water flow through cell tissues), root hairs, root-soil contact, soil rhizosphere and perirhizal hydraulic properties, soil hydraulic properties and soil layering, and climate. Based on these simulations, we investigate the emergent relationships between soil water accessibility and root zone soil water content. In agreement with experimental observations, we find that meteorological conditions have an important impact on soil water accessibility with decreasing accessibility when evaporation demand increases. A lower plant hydraulic conductance either due to lower root tissue conductance or lower root length, also reduces soil water accessibility. Loss of soil-root contact in dry soil had a strong impact on plant water potential but a low impact on soil water accessibility. The relationships between soil water accessibility and soil water content or water potential depended strongly on soil hydraulic properties. Interestingly, using relative available water content, i.e., relative to the available water content at field capacity, reduced the variability in this relation between soils considerably. Deriving the relationship assuming a uniform soil water distribution in the root zone resulted in an underestimation of soil water accessibility. Non-uniform water distribution in the root zone increased the accessibility of water in the root zone compared to case when the same amount of water is distributed uniformly.

# Trees' Effect on Soil Penetration Resistance Under Livestock-Forestry System in Southern Brazil

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## ABSTRACT

Soil moisture plays a crucial role in soil penetration resistance to the roots (PR), directly affecting plant growth and their ability to access water. Studies have indicated that soil moisture may be lower near trees in Livestock–forestry systems (Glatzle et al., 2021), influencing PR. However, there are few data demonstrating such an effect. This study aimed to verify the effect of the trees on PR under the Livestock-Forestry (LF) system. The study was conducted in a clayey Oxisol located at the Canguiri Experimental Center, belonging Federal University of Paraná, Brazil. Three treatments were studied, two defined by distances from the tree rows: 4 and 8 meters, both in the LF system, referred to as LF4 and LF8, and one randomly in the Livestock system, referred to as L. Soil penetration resistance data were collected on field using a penetrometer along two transects of 36 meters in length with 12 sampling points, taken every 3 m, down to a depth of 0.35 m, totaling 24 points per treatment. Measurements were taken close to the field capacity condition. Previously, data of soil water content, obtained under a potential of -10 kPa, were 0.45, 0.34, and 0.38 $m^3\ m^{-3}$, respectively, in L, LF4, and LF8. In addition, two Teros® 10 sensors were used to obtain soil moisture data, which remained at the experimental site from October 2024 to February 2025. It was observed that, in L, the highest mean value was found (0.32 $m^3\ m^{-3}$), decreasing by 16% in LF4 (0.27 $m^3\ m^{-3}$) and 13% in LF8 (0.28 $m^3\ m^{-3}$). PR data were processed in Microsoft Excel® software, considering the confidence interval (95%). The results indicated that in the first centimeters (0–5 cm), PR was similar among treatments, with an average of 0.43 MPa. In the L system, lower PR was observed throughout the soil profile compared to the LF, with values below 2.0 MPa down to 35 cm of depth. In LF4, values were near the critical threshold of 3.0 MPa in the 5–15 cm layer, differing from LF8. However, in the deeper layers of LF4 and LF8 was similar between them at some depths. At LF8, between 10–35 cm depth, PR values remained around 2.5 MPa. Despite the significant rainfall in the area, around 61 mm during the seven days before, the lower soil moisture at field capacity under LF4 and LF8 may have contributed to the increase in PR. Concluding that the trees contributed to decreasing the soil moisture and increasing the PR, which can affect plant growth.

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# Creating Pathways for Roots: Artificial Macropores through Compacted Subsoils

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**ABSTRACT**

Soil compaction has adverse impacts on key soil functions, including the restriction of root growth into depth. However, the presence of vertical macropores facilitates access to water and nutrient reservoirs in subsoils. While mechanical amelioration strategies are susceptible to recompaction, bio-drilling with taprooted perennial crops or earthworms has been shown to be limited meliorating compacted layers. This highlights the need for novel remediation strategies. Therefore, the use of artificial macropores as preferential pathways into the subsoil, particularly under compacted soil conditions, may restore soil functions and increase plant productivity. The objective of the present study was to assess the colonization of artificial pores with roots and anectic earthworms, as well as the effect on root depth development and yield of cereals. It is hypothesized that there will be a positive influence on root depth distribution and yield under dry growing conditions.

Two randomized and four times replicated field trials were setup in 2024 at farmers field sites in Northeastern Germany (treatments: Control and 100 artificial pores $m^{-2}$) and Central Germany (treatments: Control, 50, 100, and 200 artificial pores $m^{-2}$). In total 11.500 artificial macropores, 10 mm in diameter, were manually created down to 80 cm depth. Sampling took place in 2024 and 2025. Convolutional neural network-based image analysis was employed to analyze root depth distribution within 0-100 cm.

Across both years artificial pores led to an increase in yield by 12% for the 100 pores per square meter treatment on the loamy sand and by 2%, 3%, 5% for the 50, 100 and 200 pores per square meter treatment on the silt loam. In subsoils beneath the compacted plow horizon the artificial pores increased root length density in 50-100 cm soil depth by 110%. Results indicated higher attractiveness of artificial pores, as 88% of them were colonized with at least one root, while only 73% of biopores were colonized with roots. In 2024, 1.4% and in 2025, 3.5% of artificial pores were already colonized by anecic earthworms on the silt loam.

These findings indicate that artificial macropores constitute a promising strategy to enhance root depth distribution, water and nutrient uptake and finally yields, in soils characterized by compaction.

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# Modeling plant water and solute uptake by HYDRUS

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## ABSTRACT

Modeling plant water and nutrient uptake is a cornerstone of understanding the **Soil-Plant-Atmosphere Continuum (SPAC)** and is critical for optimizing agricultural productivity and environmental sustainability. Among the various numerical tools available, the HYDRUS software package (Šimůnek et al., 2024) has emerged as one of the most robust and widely used platforms for simulating these complex processes. This ABSTRACT explores the mechanisms, mathematical frameworks, and practical applications of modeling plant water and solute uptake using HYDRUS.

**Plant Water Uptake**

HYDRUS simulates water flow in variably saturated porous media by numerically solving the **Richards equation**. Plant root water uptake (RWU) is incorporated into this equation as a **sink term (*S*)**. The potential transpiration rate is distributed across the root zone based on the root length density distribution. However, actual water uptake is often lower than potential uptake due to environmental stresses. HYDRUS employs two primary modeling approaches to describe this reduction. On the one hand, it uses an empirical macroscopic model of Feddes et al. (1978). On the other hand, it implements three physically based models of Nimah & Hanks (1973), Couvreur et al. (2012, 2014), and de Jong van Lier et al. (2008, 2013). All three physically based RWU models can simulate processes such as hydraulic lift or compensated RWU. The model further accounts for **salinity stress** by integrating osmotic potential into the response functions. This is particularly vital in arid regions where irrigation with marginal-quality water is common.

**Plant Solute and Nutrient Uptake**

Beyond water, HYDRUS simulates the transport and uptake of solutes (e.g., nutrients like nitrates or contaminants) (Šimůnek and Hopmans, 2008). The model distinguishes between two primary mechanisms. A) **Passive Uptake:** Solutes are carried into the root system via the mass flow of water. B) **Active Uptake:** This accounts for the plant's physiological ability to absorb nutrients against concentration gradients, often modeled using **Michaelis-Menten kinetics** or specific concentration thresholds.

**Dynamic Plant Uptake Modules**

Soil pollution from neutral and ionizable compounds poses a significant threat to water resources management and food production. To address this problem, HYDRUS was coupled with a multi-compartment dynamic plant uptake model (Brunetti et al., 2019, 2021, 2022), which accounts for differentiated multiple metabolization pathways in plants' tissues. The model, which can simulate the reactive transport of neutral compounds, has been successfully validated against experimental data. HYDRUS has also been coupled with the SUGAR model (Brunetti et al., 2025), which predicts water and carbohydrate distribution within the soil-fruit system. The model can provide insights into water and carbohydrate allocation under different watering regimes, advancing predictive capabilities for sustainable crop management strategies.

**Applications and Significance**

By coupling these uptake mechanisms, HYDRUS enables researchers to predict the efficiency of fertigation, the risks of nutrient leaching to groundwater, and the impact of climate change on crop water requirements. The software's ability to handle multi-component chemistry through the **UNSATCHEM** module makes it indispensable for managing soil sodicity and salinity. Ultimately, modeling with HYDRUS provides a mechanistic understanding that bridges the gap between small-scale soil physics and field-scale agricultural management.

# Biochar application to soil in agricultural water management

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**ABSTRACT**

The problem of water shortage in agricultural production is becoming more and more noticeable, even in those parts of the world where water shortages have not occurred. Climate change, increasingly dynamic weather, and extreme phenomena such as droughts and floods pose a significant threat to the agricultural production process and its future planning. Therefore, it is essential to develop new strategies and water-saving technologies that will better enable farmers to address the challenges of modern agriculture. The FARMWISE project is dedicated to finding new solutions and tools for decision-making in the field of water management strategies and tackle the pressing challenges of water scarcity and quality in agriculture. One of the solutions being tested is the production and use of biochar as a soil additive that improves soil water properties and water retention capacity. The task aimed to invent and implement a simple tool for biochar production on-site at the farm. As well as testing the obtained biochar in field conditions and monitoring the effect of the additive on the quantity and quality of water available to plants. The results of field experiments conducted in the arable field and in the apple tree orchard clearly indicate an improvement in the sorption properties of the soil, including the ability to retain water, as well as an improvement in other soil parameters that are important for the development of the plant root system and the uptake of nutrients introduced with fertilization and irrigation. The use of 10t/ha of biochar increased water retention capacity by up to 10% in sandy soil and reduced water runoff from the soil under constant plant irrigation, which contributes to lower production costs and reduces the negative impact of agricultural production on the environment.

**Acknowledgments**

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# Assessment of irrigation water consumption in the Yellow River Delta based on GIS and HYDRUS-1D

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**ABSTRACT**

Irrigation is essential for sustaining crop productivity and agricultural sustainability in saline–alkali farmlands, but it also intensifies the contradiction between freshwater supply and demand in water-scarce regions. In the Yellow River Delta (YRD), widely distributed saline soils with pronounced spatial–temporal heterogeneity and shallow saline groundwater strongly alter water–salt dynamics in the crop root zone. This results in large regional differences in unit irrigation water consumption (UIWC), creating challenges for accurately estimating regional irrigation demand and optimizing cropping structures to reduce irrigation pressure. Hydrological, meteorological, soil, and crop growth data of the YRD from 2021 to 2022 were collected using ArcGIS 10.8.2. Five dominant cropping structures across 17 townships—winter wheat–summer maize, winter wheat–summer soybean, rice, and cotton—were selected as research objects. The HYDRUS-1D model was employed to quantify the UIWC under current cropping systems, and spatial distribution maps of UIWC and regional water use efficiency (WUE) were generated. The results indicated that the pre-sowing root-zone salt leaching requirement across the entire region ranged from $1.13 \times 10^8$ to $1.59 \times 10^8$ m³, showing a significant discrepancy compared with estimates derived from empirical formulas. Substantial spatial variation in unit irrigation water consumption (UIWC) was observed among townships, with coastal areas requiring considerably higher irrigation due to higher soil salinity and more saline shallow groundwater. In some moderately to severely saline soils, the pre-sowing leaching requirement for summer maize–winter wheat and spring maize even exceeded the irrigation demand during the growing season. Grain crops (wheat and maize) exhibited the highest irrigation demand, accounting for 79.3% of the total, whereas cotton required the least (11.4%) owing to its strong salt tolerance and the coincidence of its growing season with the regional rainy period. Overall, the total irrigation demand under the current cropping structure reached $6.65 \times 10^8$ m³, whereas the actual water supply was only $2.7 \times 10^8$ m³, resulting in a substantial deficit of approximately $3.9 \times 10^8$ m³. These findings demonstrate that, under the current cropping structure, the YRD is highly vulnerable to irrigation deficit, yield reduction, and aggravated soil salinization. Optimizing cropping structures and improving irrigation efficiency are therefore critical strategies to alleviate regional water scarcity, safeguard food security, and promote sustainable agricultural development in saline–alkali regions.

# Stress-Strain Mechanism of Salt-affected Soils in the Yellow River Delta

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**ABSTRACT**

The continuous increase in agricultural mechanization has led to intensified soil compaction degradation. It is crucial for ensuring the sustainable development of national agriculture by addressing soil compaction. Salt-affected soils, which are important reserves for arable lands, have experienced an increase in agricultural use in response to national demand in China, leading to an increased soil compaction risk. However, current research on soil compaction is mainly focused on non salt-affected soils, resulting in a lack of understanding of the compaction process under salt-affected soils. To address this gap, this project will focus on the Yellow River Delta farmland ecosystem. By a combination of incubation experiment, field experiments, and model simulation, this report aims to talk the following objectives: 1) Study the stress distribution, transmission, and soil strain characteristics of soil mechanical compaction process in farmland with different saline gradients. This will clarify the salt-affected soil compaction process and reveal the mechanism behind salt-affected soil compaction. 2) Based on the soil stress-strain characteristics of the study area, combine the annual seasonal dynamics of soil moisture and the development trend of farming machine types, it will enable the construction of a soil compaction model of the study area and predict the spatial and temporal trends of soil compaction risk in regional farmlands. The research results will have significant scientific and practical value in understanding the occurrence mechanism of soil compaction and prevention of farmland risk in the Yellow River Delta.

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# Impact of drought and root excision on root regeneration, xylem hydraulics and leaf physiological characteristics in Robinia pseudoacacia

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**ABSTRACT**

Underground mining subsidence can induce alterations in the vadose zone structure, resulting in direct root damage and a reduction in available water, which pose threats to plant survival. Nevertheless, the impacts of these stress factors on root xylem hydraulic conductivity and leaf water metabolism still remain ambiguous. This study explored the influences of different drought intensities (no drought, moderate, severe) and root excision intensities (0%, 25%, 50%) on the root characteristics, xylem hydraulic conductivity, and leaf physiology of Robinia pseudoacacia. The results show that the fine root length and fine root mass fully recuperated to pre-stress levels within one month under all treatment conditions at the whole-plant scale. However, density-based analysis indicated that stress augmented fine root proliferation in the non-excised area, and root excision predominantly regulated fine root length density and fine root mass density. The percentage loss of xylem hydraulic conductivity, maximum xylem specific hydraulic conductivity, leaf water potential, and leaf gas exchange parameters were influenced by drought stress and root excision. Relative contribution analysis indicated that drought stress exerted the most substantial influence on xylem hydraulic characteristics. Conversely, regarding leaf physiological properties, apart from the effect of drought stress, the interaction between drought stress and root excision also made a notable contribution. Overall, fine root regeneration alleviated the impacts of excision, emphasizing soil water deficit as the key limiting factor. Considering that most coal resources are situated in arid regions and the drought is intensifying due to climate change, giving priority to drought mitigation is essential for preventing post-subside vegetation degradation.

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# Improvement of the Soil Water Retention Model Based on the Additivity Hypothesis

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**ABSTRACT**

The current processes of climate change, as well as agriculture, lead to both positive and negative changes in soil health. To prevent the negative impacts of soil degradation and to restore degraded soils, practice-oriented solutions are needed for sustainable food production as well as for the quality of environmental services. This requires knowledge of how soil water regimes are formed, including the control of infiltration and runoff, the effects of water erosion, deep percolation, and lessivage. Recent advances in understanding the relationship between soil hydrological and biogeochemical processes allow for further improvement of models that link soil water regimes and hydraulic functions, depending on soil structure, texture, and organic matter content (SOM).

In this context, it is of considerable interest to model the effect of changes in SOM on soils with different structures and textures regarding the amount of water available for agricultural plants. To this end, a previously proposed model for estimating soil water retention (SWR) based on the additivity hypothesis was improved by including two parameters: SOM and the density of soil aggregates. To verify this model, we used datasets from laboratory experiments conducted on samples with Montluel soil monoaggregates, as well as samples of soil aggregates.

The analysis of results obtained from Montluel soil samples allowed us to test the effects of soil compaction on interaggregate and intraaggregate porosity, as well as their influence on SWR. Testing the model on samples of aggregate fractions enabled us to examine the effects of soil aggregate size on interaggregate and intraaggregate porosity, as well as on SWR. Additionally, using datasets of SWR included in the UNSODA database, we compared the results of the improved model with those obtained from several common regression models known as pedotransfer functions for estimating SWR.

It was shown that the effect of SOM on SWR is not uniform across different soil textures. For soils with coarse textures, the influence of SOM leads to more significant changes in SWR than for soils with a high content of fine fractions. Thus, the results indicate, on one hand, an improvement in the predictive description of SWR using an enhanced additive model, and on the other hand, highlight the need for further research—especially by distinguishing between two fractions of SOM: particulate organic matter and mineral-associated organic matter.

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# Adaptive water use strategies of artificially revegetated plants in a water-limited desert: Implications for sustainable ecological restoration

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**ABSTRACT**

Understanding the water use patterns of artificially revegetated plants in arid and semi-arid desert regions with shallow groundwater is crucial for sustainable water resource management and effective vegetation restoration strategies. Despite extensive vegetation rehabilitation in China's Mu Us Sandy Land, the interspecific and seasonal variations in plant water sources under similar groundwater conditions remain unclear. We conducted isotopic analysis of hydrogen and oxygen in main sand-fixing plants—*Pinus sylvestris var. mongolica*, *Amygdalus pcdunculata Pall*, and *Artemisia desertorum Spreng*—alongside potential water sources during the three growing seasons. Our aim was to elucidate seasonal changes in plant water uptake patterns by correcting isotopic offsets in xylem water using the MixSIAR model. Results indicated that *A. desertorum* predominantly utilized water from the 0–150 cm soil layer (67.52±14.44 %) throughout all seasons. Conversely, P. sylvestris and *A. pedunculata* shifted their primary water sources from the 60–240 cm soil layer during the dry season (55.20±2.12 and 57.96±1.45 %, respectively) to the 0–150 cm soil layer during the rainy season (68.44±4.46 and 66.19±1.68 %, respectively), suggesting greater water uptake adaptability in trees and shrubs compared to grasses. Groundwater contribution to plant water uptake showed no significant interspecies difference during the rainy season ($P > 0.05$). However, *P. sylvestris* and *A. pedunculata* significantly increased groundwater absorption during the dry season compared to the rainy season ($P < 0.05$). Correcting $\delta^2H$ offsets in xylem water revealed an underestimation of groundwater contributions by 16.06±9.09 % in the dry season and 4.25±0.55 % in the rainy season. Given these interspecific and seasonal variations in water uptake patterns among sand-fixing plants, and the imperative for sustainable groundwater use, tailored water management strategies are essential to prevent the degradation of restored ecosystems in this water-limited desert region.

**Acknowledgments**

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# Evolution of Salt Precipitation: Governing Water and Heat Transport in Saline Soils

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## ABSTRACT

Salt precipitation, a common phenomenon in saline soils, significantly influences water and heat transport—a subject that has attracted considerable research attention. However, the specific mechanisms and effects of salt precipitation on these processes remain unclear. In this study, we investigate the evolution of salt precipitation and its impact on evaporation and soil temperature under varying soil textures, evaporation demands, salt types, and hydraulic conditions, using combined experimental and numerical simulation approaches. Results show that salt crust patterns vary with soil texture. In finer-textured soils (silt loam), thin, flat, and uniform salt crusts develop, offering greater resistance to evaporation. In contrast, coarser soils form thick, rough salt crusts with lower evaporation resistance. Sodium sulfate tends to precipitate as sub-florescence during soil drying, whereas sodium chloride primarily forms efflorescence. Under high evaporation demand, fine powder-like crystals precipitate uniformly, while under low evaporation demand, discrete and larger crystals are observed. Salt crusts notably increase soil temperature, with temperature dynamics being closely linked to crust evolution. The elevated temperature in saline soils compared to salt-free soils is attributed to several factors: reduced heat loss due to higher evaporation resistance and lower surface emissivity of the salt crust, very low thermal resistance of the crust itself, heat release during saline solution crystallization, and lower soil heat capacity. These findings enhance the understanding of water and heat balance in saline soils under evolving salt precipitation conditions.

# Field-scale Assessments of Subsoil Compaction and Soil Structural Functions in Lower Saxony, Germany

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**ABSTRACT**

Subsoil compaction a one of the major threats for crop production and soil ecological functioning in Europe. To quantify its field-scale extent, field investigations were conducted on 26 agricultural fields across Lower Saxony state in northern Germany, covering four dominant soil textures (clay loam, sandy loam, silt, and silty loam) and two field management zones (machinery turning area and main field area). In-situ measurements of penetration resistance and shear strength were conducted on field at 10 cm (topsoil) and 40 cm (subsoil), and bulk density (ρb), saturated hydraulic conductivity (Ks), air permeability (Ka) were measured on undisturbed soil samples at the same depth. The results showed that most machinery turning zones showed clear signs of subsoil compaction. About 80% fields showed 5~60% higher penetration resistance and shear resistance in machinery turning area. For sandy loam soil in the east and north part of Lower Saxony, penetration resistance frequently exceeded 3 MPa, reaching >5 MPa at 40 cm, which is above root limiting thresholds. Compared to main field zone, bulk density in machinery turning area increased by 2-5%, with silty loam field exhibiting the largest increase of bulk density. Additionally, soil pore functions of Ka and Ks in machinery turning area exhibited obvious decline compared to field area especially in the subsoil of silty loam and sandy loam fields. For both machinery turning area and field area, a significant correlation was found between hydraulic conductivity and soil bulk density (R2=0.21, p=0.023) in topsoil with ρb from 1.25~1.60 g cm-3, while in subsoil with ρb from 1.45~1.65 g cm-3 no such correlation was found, indicating the pore functions in subsoil mainly depends on connective pores during the structure formation process. These results demonstrate that traffic-induced subsoil compaction is widely altering soil physical structure and pore functions in Lower Saxony, and the texture-dependent responses highlight the need for specific compaction mitigation strategies during the future field managements.

**Keywords:** Subsoil compaction, Soil structure, Hydraulic conductivity, Penetration resistance

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# Soil Pore Size Distribution and Water Retention Curves by Low-Field NMR

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## ABSTRACT

Freshwater scarcity is a preeminent global challenge, with agriculture alone accounting for 70% of total consumption. A soil's capacity to retain water, filter solutes, and recharge aquifers is dictated by its **Soil Water Retention Curve (SWRC)**. As a fundamental property in soil physics, the SWRC—alongside pore size distribution—is essential for modeling fluid and solute transport within the vadose zone. These properties have critical implications across agriculture, forestry, ecology, and civil engineering.

**The Current Bottleneck**

Despite their importance, quantifying soil hydraulic properties remains a significant challenge. Conventional empirical methods, such as porous plates and pressure cells, are:

- **Laborious and time-consuming:** Often taking days or weeks.
- **Expensive:** Requiring specialised, high-maintenance equipment.
- **Prone to error:** Susceptible to operator bias and experimental inaccuracies.

These limitations make hydraulic characterisation the primary bottleneck in soil physics laboratories worldwide.

**A New Analytical Frontier: NMR Relaxometry**

While $^1$H Nuclear Magnetic Resonance (NMR) relaxometry has been used to characterise soil porosity, it often presents an "ill-posed problem." Traditional spin-lattice and spin-spin relaxometry results are confounded by two correlated unknowns: **pore length scales** and **surface relaxivity**.

To overcome this, we propose a method that directly accesses **NMR diffusion modes**. This approach is governed solely by pore size, making it independent of unknown surface relaxivity. Our refined low-field NMR method is:

- **Fast:** Delivers results in under 90 minutes.
- **Precise:** Provides unprecedented resolution and accuracy.
- **Comprehensive:** Simultaneously determines pore size distribution, the SWRC, and hydraulic conductivity.

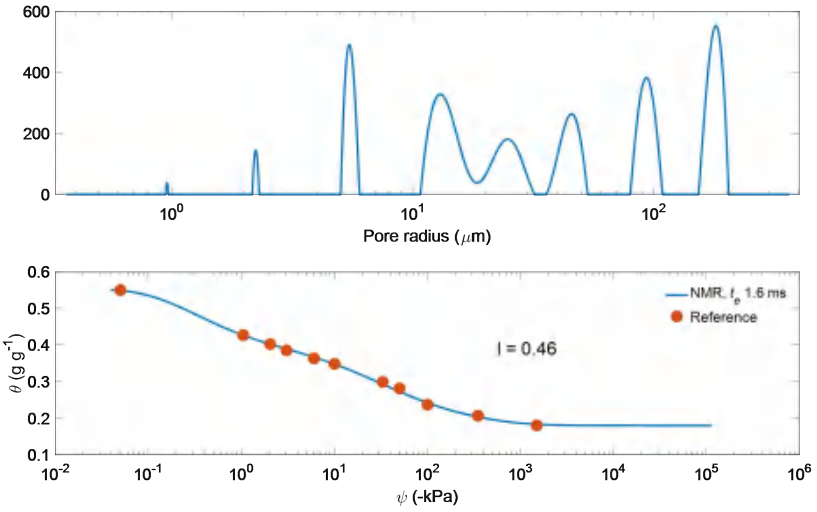
**Validation and Results**

We evaluated an optimised, more robust and elegant pulse sequence on 21 challenging soil samples (including Gleyic and Vertic). After saturation and thermal stabilisation, the samples were analysed using the **DIFF method**. The results confirm that this approach accurately determines pore size distribution and estimates water retention curves in a fraction of the time required by conventional techniques (Figure).

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Text improved by Gemini (AI).

Figure: Pore size distribution and soil water retention curve for an Alumic Plinthic Gleysol from Amazon-Brazil. NMR: the proposed method. References: combination of tension table; pressure plate extractor and dewpoint potentiometer. l: tortuosity index.



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# Collaborative roles of soil and plant hydraulic resistances in plant water transport: insights from modeling and data synthesis

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**ABSTRACT**

Soil-plant water transport is a fundamental hydrophysiological process in terrestrial ecosystems. While factors influencing this process under drought stress have been increasingly identified, their interactive effects remain poorly understood. In this study, we combined literature synthesis with a process-based soil-plant water transport model to investigate how key hydraulic traits, including stomatal sensitivity, soil texture, and plant hydraulic vulnerability, jointly shape plant drought responses. In particular, we focused on how the combined effects of these traits influence the relationship between soil and leaf water potentials ($\psi_{soil}$-$\psi_{leaf}$), mediating the expression of isohydric versus anisohydric strategies. Our results demonstrate that plants with greater stomatal sensitivity to $\psi_{leaf}$ also respond more strongly to variations in $\psi_{soil}$ and exhibit smaller reductions in soil-plant hydraulic conductivity($K_{sp}$). Beyond stomatal sensitivity, rhizospheric hydraulic conductivity ($K_{rhizosphere}$) influences soil-plant water transport, and its influence varies with soil texture. The higher hydraulic conductivity of loam soils compared with sand soils amplifies the influence of $K_{rhizosphere}$ variability on transpiration, stomatal conductance, and $K_{sp}$. The $\psi_{leaf}$-$\psi_{soil}$ relation shows plants characterized by low stomatal sensitivity, high vulnerability in $K_{sp}$, and sand soil planting conditions tend to exhibit greater divergence between $\psi_{leaf}$ and $\psi_{soil}$, leaning towards an anisohydric behavior. These findings suggest that the $\psi_{leaf}$-$\psi_{soil}$ relation arises not from individual hydraulic components in isolation, but from their integrated interactions. This underscores the importance of a systems-level perspective in soil-plant water transport and supports the development of integrative frameworks to better predict plant responses under intensifying drought conditions.

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# Mucilage effects on soil–plant hydraulics and stomatal regulation under drought

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## ABSTRACT

Plants respond to soil and atmospheric water deficits through strategies such as stomatal regulation and belowground adaptations. Root mucilage buffers erratic fluctuations in rhizosphere water content, yet its influence on soil hydraulic properties, especially unsaturated hydraulic conductivity, and stomatal regulation remains unknown. We hypothesized that mucilage facilitates water uptake by attenuating the drop in matric potential at the root-soil interface during soil and atmospheric drying. We measured the impact of various maize mucilage contents (0.0%, 0.05%, 0.2%, and 0.4%) on the water retention and hydraulic conductivity of a loamy soil. Leveraging a soil-plant hydraulic model, we investigated the effects of mucilage contents on transpiration and stomatal responses under soil drying and increased vapor pressure deficit (VPD). Higher mucilage contents prevented sharp declines in unsaturated hydraulic conductivity as soils dried. Simulations revealed that higher mucilage contents delayed the onset of hydraulic stress (the threshold transpiration rate beyond which small increase in transpiration would result in a disproportional decline in leaf water potential), broadened the hydroscape zone, and shifted stomatal behavior from isohydric to more anisohydric regulation, enabling plants to sustain stable transpiration and lower midday leaf water potentials under drought. The buffering effects on soil-plant hydraulics were persistent across varying VPD, although high mucilage contents accelerated soil drying, indicating a trade-off between improved water uptake and faster moisture depletion during prolonged drought. Our findings underscore the important role of mucilage in modulating soil-plant water relations and stomatal regulation, offering insights into strategies for improving plant response to soil and atmospheric drought.

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# Study on the Impact of River-Sea Position on Water Sources of Tamarix chinensis Vegetation in the Yellow River Delta

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## ABSTRACT

Wetlands play an irreplaceable role in climate regulation, water conservation, and biodiversity protection, earning them the title of "kidneys of the Earth." Coastal wetlands, located in the land-sea ecotone and subject to the interactive forces of terrestrial and marine processes, are highly sensitive to external disturbances and represent globally sensitive and fragile ecosystems under environmental change, exhibiting distinct regional characteristics. The Yellow River Delta, as the world's most intact, typical, and youngest warm temperate wetland ecosystem, is situated in a unique geographical location where land, sea, and river interactions occur. This has led to the formation of a notably ecologically vulnerable and sensitive zone, characterized by high dynamism and complexity, making it representative on a global scale.

Tamarix chinensis, as a dominant and constructive species in the Yellow River Delta, possesses traits such as salt tolerance, alkali tolerance, resilience to barren soils, and drought resistance. It serves as a pioneer and key species for saline-alkali land improvement and ecological restoration in coastal wetlands of the region. However, existing research has largely focused on the growth characteristics and stress resistance physiology of Tamarix chinensis, with limited systematic investigation into its water-use strategies and sources. In recent years, hydrogen and oxygen stable isotope techniques have been widely applied in studies of plant water sources due to their minimal destructiveness to plants and high data reliability. Except for a few xerophytic and halophytic plants that may exhibit hydrogen stable isotope fractionation during root water uptake, most plants do not undergo stable isotope fractionation. Therefore, by comparing the stable isotope values of plant stem xylem water with those of potential water sources, the proportional contributions of various water sources to plant uptake can be estimated.

Accordingly, this study takes Tamarix chinensis populations at different land-sea locations in the Yellow River Delta as research subjects. Using stable isotope techniques, we measure the spatial variations in $\delta^2H$ and $\delta^{18}O$ values in xylem water of Tamarix chinensis and potential water sources. The MixSIAR model is employed to calculate the contribution proportions of potential water sources to Tamarix chinensis, aiming to investigate the adaptation mechanisms of Tamarix chinensis to varying water conditions across different habitats.

The Yellow River Delta (36.33°N–38.10°N, 117.19°E–119.11°E), situated in northeastern Shandong Province and bordering the Bohai Sea and Laizhou Bay, is the largest, youngest, and most rapidly developing typical river estuary delta in China. This study focuses on its eastern coastal area and the Yellow River estuary region (37°40′–38°10′N, 118°41′–119°16′E). The area experiences a warm-temperate semi-humid continental monsoon climate, characterized by four distinct seasons with pronounced differences in temperature and humidity between cold/dry and hot/wet periods. The mean annual temperature is 12.6°C, and the mean annual precipitation is 543.2 mm.The Yellow River, as the primary exogenous river, serves as the main source of freshwater resources for the region. The groundwater table is shallow (1–2 m) with high salinity, generally ranging from 5 to 20 g/L. Its main recharge sources are precipitation, river infiltration, and lateral seawater intrusion. The terrain is predominantly low-lying (mostly below 15 m in elevation). Seawater intrusion and lateral infiltration contribute to a raised groundwater table, which readily triggers soil salinization.

Influenced by factors such as historic shifts of the Yellow River course and marine erosion, the soils are primarily Fluvo-aquic soils and Saline soils. Saline soils are distributed in a belt-like pattern along the coast, accounting for 36.16% of the total soil area, with surface soil salt content ranging from 0.8% to 2.0%. Sandy soils are predominant along the Yellow River banks, gradually transitioning to loam and clay soils inland.Within the study area, the halophyte Tamarix chinensis is widely distributed. It is frequently associated with companion species such as Suaeda glauca, Suaeda salsa, Phragmites australis, Artemisia scoparia, Sonchus wightianus, Setaria viridis, and Cynanchum chinense.

In the eastern region of the Yellow River Delta, six typical, continuous, and minimally human-disturbed Tamarix populations (aged 8–10 years) were selected along the Yellow River and near its estuary. These sites, labeled sequentially from sea to land as A, B, C, D, E, and F (Fig. 1), were equipped with two sets of thermal dissipation probes (TDP-30, Dynamax Inc., Houston, Texas, USA) installed in the 0–90 cm soil layer beneath the Tamarix canopy at each site prior to the initiation of field research. The probes were used for hourly automated monitoring of soil moisture and electrical conductivity. Additionally, a groundwater observation well was installed near the center of each site to monitor groundwater dynamics, and global positioning system (GPS) coordinates were recorded for all sampling locations.

During the peak growing season of the shrubs, investigations were conducted on Tamarix populations near the probe installations. Uniformly growing individuals were selected at each site, and root samples were collected using a root drilling method at three directions 30 cm from the base of each plant. An 85 mm diameter root drill was employed to collect samples at intervals of every 10 cm within the 0–50 cm depth and every 20 cm below 50 cm, down to a depth of 130 cm. Simultaneously, a soil profile of 1.3 m depth was excavated at each site, and 100 $cm^3$ soil cores as well as stratified soil samples were collected following the same depth intervals. In each quadrat, select three Tamarix plants and collect fully suberized two- or three-year-old branches from each plant. Using pruning shears, excise the branches into 5-cm segments, remove the phloem, and retain the xylem. Immediately place the segments into a capped glass sample vial and seal the opening with Parafilm. Repeat this sampling procedure three times per sampling point. Within a 1-m radius around each selected Tamarix individual, collect soil samples with a 4.5-cm diameter auger from the following depth intervals: 0–20 cm, 20–40 cm, 40–60 cm, and 60–100 cm. Transfer the collected soil samples promptly into capped glass vials. Simultaneously, collect groundwater samples and seal all vials with Parafilm. Subsequently, store the plant and soil samples at –10 °C, and preserve the groundwater samples at 4 °C.

All soil and plant samples were transported to the laboratory for systematic physicochemical analysis.

Based on the comparison of isotopic signatures between soil water and plant xylem water, the ranges where their isotopic values are similar or overlapping can be considered as potential water sources for the plants. As shown in Figure 2, influenced by their varying distances from the river and the sea, the water-use strategies of Tamarix plants differ across sampling sites. At site A, Tamarix primarily absorbs soil water from around the 50 cm depth. With decreasing distance from the Yellow River, the water source for Tamarix at site B shifts gradually toward the 50~100 cm soil layer. The xylem water isotopes of sites D and C show significant overlap with those of shallow soil water at 20~60 cm, indicating that these sites mainly rely on water from this layer. In contrast, Tamarix at site E predominantly utilizes deeper soil water from the 60~100 cm layer. Meanwhile, at site F, the xylem water isotopes overlap repeatedly with soil water isotopes across the 20~100 cm profile, suggesting that Tamarix at this site exploits water more evenly from different soil depths.

Due to the occurrence of hydrogen stable isotope fractionation during water uptake by roots of xerophytic or halophytic plants, while oxygen stable isotopes do not fractionate, this study used only $\delta^{18}O$ values to calculate the water contribution ratios. As shown in Figure 3, the proportion of water use from different soil layers by Tamarix plants exhibited significant spatial heterogeneity across the sampling sites. Overall, the contribution ratios of the 0–20 cm, 20–60 cm, and 60–100 cm soil layers ranged from 11.1% to 33.0%, 28.3% to 60.6%, and 28.3% to 53.0%, respectively. At the individual site level, water use patterns varied distinctly with depth: sites A, B, C, and E showed the lowest contributions from the shallow 0–20 cm soil layer, at 11.1%, 20.9%, 21.9%, and 17.6%, respectively. Among these, site A recorded the highest contribution from the 20–60 cm layer (60.6%), while sites B and C also peaked in this layer (39.1% and 40.4%, respectively). In contrast, site E derived its highest water contribution from the 60–100 cm layer (53.0%). Site D exhibited the lowest contribution from the 20–60 cm layer (28.3%) and the highest from the 60–100 cm layer (42.9%). Site F demonstrated relatively even water uptake across depths, with a cumulative contribution from the 0–60 cm layers (0–20 cm + 20–60 cm) of 66.2%, which was higher than that from the 60–100 cm layer (33.8%). In summary, site F relied predominantly on shallow soil water, site A primarily utilized water from the 20–60 cm layer, and site E showed a pronounced dependence on the middle to deep soil water (60–100 cm), reflecting its distinctive water acquisition strategy.

Based on the relationships among root distribution, water sources, and soil water–salinity environments at various sampling sites (Fig. 4), the water uptake strategies of Tamarix plants differed markedly across locations. At site A (7.78 km from the river, 20.73 km from the sea), where influence from both river and sea was weak, the shallow soil moisture was only 28.24% and salinity reached 15.52 $g \cdot kg^{-1}$, creating pronounced water and salt stress. This led to reduced root proliferation in shallow soil and concentration of roots in the 20–60 cm layer. As a result, water uptake from shallow soil was minimal (11.1%), while uptake from the middle layer accounted for 60.6% of the total, reflecting an avoidance strategy under high salinity and low water availability in surface soil.

At site B (0.32 km from the river, 22.03 km from the sea), located close to the Yellow River, balanced water–salt conditions supported relatively uniform root distribution in the middle to deep layers (20–100 cm), with similar water uptake proportions from these layers (39.1% and 39.9%). Site C (4.77 km from the river, 14.29 km from the sea), situated in a zone with moderate river and sea influence, exhibited mild water–salt conditions. Roots were distributed relatively evenly in the 20–100 cm profile, and water uptake proportions across layers were comparable (21.9%, 37.7%, and 40.4%), with only slightly lower uptake from the surface due to elevated salinity.

At site E (9.21 km from the river, 7.02 km from the sea), distant from the Yellow River and with limited freshwater recharge, vertical differentiation in water and salt conditions was pronounced. Roots extended significantly into the deep layer (60–100 cm), where water uptake reached 53.0%. Site F (0.31 km from the river, 1.22 km from the sea), influenced by both river freshwater and seawater intrusion, showed even root distribution in the 20–100 cm profile, with nearly equal water uptake from shallow, middle, and deep layers (33.0%, 33.2%, and 33.8%).

Site D (3.15 km from the river, 6.30 km from the sea) lies in a sensitive river–sea interaction zone. Surface soil (0–20 cm) salinity was as high as 19.91 $g \cdot kg^{-1}$, imposing strong salt stress, while the deep layer (60–100 cm) exhibited favorable conditions with 52.34% moisture and reduced salinity (15.90 $g \cdot kg^{-1}$). Correspondingly, roots extended substantially into the 60–100 cm layer, from which water uptake contributed 42.9% of the total—thereby avoiding high surface salinity while accessing stable water from deeper soil.

Overall, these patterns illustrate how root distribution and water uptake strategies in Tamarix are direct responses to local water–salt conditions shaped by varying distances from the river and the sea.

This study reveals that the varying distances from the river and the sea in the Yellow River Delta shape heterogeneous hydro-salinity conditions, which further influence the root distribution and water-use strategies of Tamarix plants. In areas close to the river, where water and salinity conditions are relatively balanced, roots are evenly distributed in the middle to deep soil layers, allowing for balanced water uptake across different depths. In coastal zones and river-sea interaction areas, high surface salinity drives root proliferation into deeper soil layers, leading to a preferential use of deeper, low-salinity water. In sites distant from both the river and the sea, dual stressors of water scarcity and salinity lead to roots concentrating in the middle soil layers where moisture conditions are more favorable, resulting in a water-use pattern centered on middle-depth soil water. Tamarix thus adapts to local hydro-salinity stress through plasticity in rooting depth. The findings provide theoretical support and practical guidance for the conservation and ecological restoration of wetland vegetation in the Yellow River Delta.



Figure1. Study area and sampling points



Figure2. The profile variations of δ2H and δ18O in soil water from different sampling sites of Tamarix populations and their relationship with xylem water isotopes. The solid line represents soil water isotopes, and the dashed line represents xylem water isotopes



Figure 3. Water source contribution rate of each soil layer at different sampling points



Figure 4. Correlation characteristic diagram of root mass density, soil salt content, and water source contribution rate of different soil layers in Tamarix chinensis at different sampling points

# HYDRUS-2D-based Study on the Impact of Drip Irrigation and Soil Compaction on Soil Water and Salt Movement

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**ABSTRACT**

The Yellow River Delta faces severe soil salinization challenges driven by shallow groundwater tables and intensive evaporation. Conventional flood irrigation (FI) not only results in significant water wastage but also exacerbates the salinization process. Saving water and controlling salt is an important means to solve practical problems in local agriculture. The advantages of drip irrigation(DI) in water saving and salt control have been widely confirmed in recent years, but there is still a lack of in-depth research on the regulatory effect of soil compaction(SC) on water and salt migration, especially its synergistic mechanism with drip irrigation.This study used soil data collected from two consecutive years of cotton field experiments to obtain soil hydraulic parameters and solute transport parameters through the construction of a Hydrus-2D model. Three simulation scenarios were established:FI, FI+SC, and DI+SC. It has been verified that the model parameters can better simulate the soil water and salt migration in the cotton root zone in this area.Simulation results show that SC reduces soil hydraulic conductivity by reducing soil pores, inhibiting the capillary rise of deep high-salinity groundwater, thereby reducing evaporation and salt return. However, FI+SC was prone to prolonged surface ponding, which hindered effective root water uptake. In contrast, the DI+SC configuration, characterized by a low-flow and high-frequency irrigation regime, delivered water directly to the crop root zone. It reduces the waste of water resources caused by evaporation and improves water utilization efficiency. At the same time, the compacted layer can prevent deep high-salinity groundwater from going up, and the effect of water saving and salt control is significant. The results of this study can provide scientific basis and decision-making support for water conservation and salt control in saline-alkali farmland in the Yellow River Delta region.

**Keywords:** Yellow River Delta; drip irrigation; soil compaction; HYDRUS-2D

# From Laboratory to Field: Advancing Soil Heat Flux Plate Accuracy through Philip Correction and Field Calibration

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## ABSTRACT

Soil heat flux plates (SHFPs) are widely used for measuring soil heat flux ($G$); however, they are prone to significant errors due to differences in thermal conductivity between the plate and soil, thermal contact resistance, and water flow divergence. This study synthesizes findings from two methodological approaches—laboratory-based physical correction and field-based empirical calibration—to evaluate the effectiveness of improving SHFP accuracy.

First, the application of the **Philip correction** was evaluated using laboratory experiments with agar-stabilized water to eliminate thermal contact resistance. Results showed that manufacturer-specified thermal conductivity values ($\lambda_p$) and plate dimensions often deviated from measured values. The Philip correction, particularly using the full plate geometry function ($H$), improved the estimation of $G$ for plates with thermal conductivities mismatched to the medium. However, in field conditions under a full maize canopy, the Philip correction only partially reduced errors. While using measured $\lambda_p$ and the full $H$ expression improved agreement with the References gradient method, significant underestimations (38%-62%) persisted due to unaccounted factors like variable soil-plate contact.

Second, a **field calibration method** was assessed as a comprehensive solution. This method utilized a short calibration period (5 days) to determine a correction coefficient based on the ratio of raw plate measurements to the References soil heat flux ($G_{s_grad}$). Remarkably, this simple linear correction accounted for almost all types of errors (including contact resistance and heat flow divergence). When applied to evaluation periods of 60–80 days, the field-calibrated values ($G_{p_corr}$) showed excellent agreement with $G_{s_grad}$ , with slopes approaching 1:1 and RMSE reductions exceeding 60%.

The comparison demonstrates that while the Philip correction addresses specific physical distortions, it is limited by uncertainties in plate parameters. Conversely, the field calibration method provides a robust, practical solution for achieving high accuracy in long-term field measurements without requiring detailed knowledge of plate properties or soil physics.

**Keywords:** Soil Heat Flux Plate, Philip Correction, Field Calibration, Thermal Conductivity, Gradient Method.

**Acknowledgments**

Acknowledgment This work is supported by the National Science Foundation under Grant 1623806, Army Research Office under Grant W911NF-16-1-0287, USDA-NIFA, Multi-State Project 3188, Iowa State University, Department of Agronomy, the Hatch Act, State of Iowa funds, State Scholarship Fund from China Scholarship Council (201608320197), and Jiangsu Province graduate education innovation project (KYLX16_0943); National Natural Science Foundation of China (NSFC) under Grants 42401012, the National Key R&D Project of China (2022YFF1300403), the U.S. National Science Foundation under Grant 2037504, and USDA-NIFA Multi-State Project 5188, Iowa State University Department of Agronomy, the Hatch Act, and State of Iowa Funds.

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# Pore systems and functions in structured soils- how far affect soil management and environmental impacts an unambiguous assignment?

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## ABSTRACT

Geogenic, pedogenic, and anthropogenic impacts affect soils concerning their chemical, physical and biological properties and functions and their rigidity or resilience and sustainability. Under energetic aspects (Fig.1) can we define the various affecting potentials for structure formation, their rigidity and the multitude of dependencies.

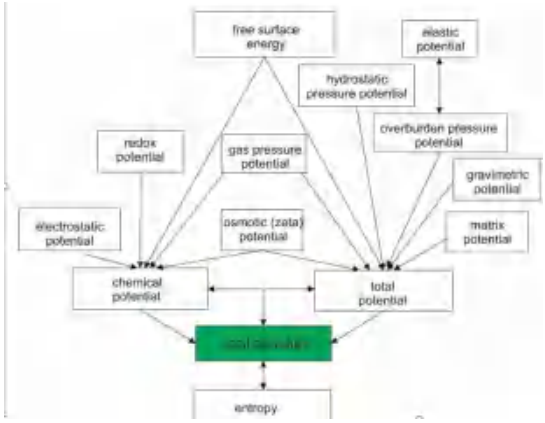



Fig.1: Energy concept influencing structure formation (slightly modified with courtesy of Zimmermann 2022)

It is furthermore well-known, that hydraulic, mechanical but also thermal processes (via osmotic, hydrophobic, surface tension and viscosity impacts) are all coupled and control on the macro- and microscale particle arrangements and aggregation as well as the accessibility of pores and their continuity including the often-available capillary barrier effects. The link between mechanical strength and accessibility of particle surfaces e.g. documents the dependency on aggregation but during shrinkage and swelling undergo the newly formed aggregates intense lateral compression and vertical shear as well as lateral displacement which all alter the pore accessibility as well as their filter and buffer capacity. Thus, the statement must be restricted only to the rigidity limits defined e.g. by precompression stress as the transition from recompression stress to the virgin compression load range (defined by mechanical processes) or the previous minimal water potential which defines the transition from the structural shrinkage to proportional shrinkage (hydraulic processes). If the aggregate-related strength “history as a site-specific memory” is exceeded by actual hydraulic ,thermal, mechanical or chemical, biological impacts, ), a new proportional shrinkage results in a contraction of the aggregated soil volume, followed by new crack formation and smaller but stronger aggregates that have, however, altered soil properties and functions. Consequently, also the often-predicted climate change impacts cause corresponding further more intense drying with stronger (more rigid) structure but consecutive changes in pore continuity and accessibility or availability of pore water etc. Fig. 2 shows the impacts of various stresses on changes in the saturated hydraulic conductivity and consequences on flux processes.

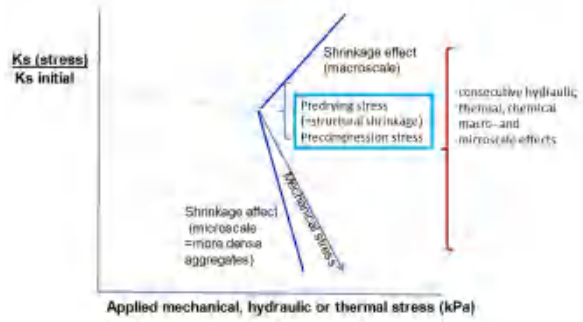



Fig. 2 Impact of stresses on changes in saturated hydraulic conductivity.

During the oral presentation will these interactions be discussed and consequences for modelling and predictability of processes as well as further research approaches analyzed.

Literature:

Horn, R., Fleige, H., Dörner, J., Zimmermann,I. Wendroth,O.2025 .Pore rigidity as an undervalued process in soil structure development. Soil and Tillage Research Volume 245, https ://doi.org/10.1016/j.still.2024.106280

Beck-Broichsitter,S., Fleige,H., Dörner,J., Horn.R. 2023 **Direction-dependency of soil hydraulic and mechanical properties** Encyclopedia of Soils in the Environment 2nd Edition ISBN: 9780128229743

# From Sedimentation to Laser Diffraction: A New Particle Size Distribution Classification Based on Soil Mechanical Properties

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**ABSTRACT**

*Background*: Modern studies demonstrate that determining soil texture classes according to Kachinsky (Russian classification) and USDA/FAO systems using particle size distribution data obtained by laser diffraction method leads to errors of 43% and 65%, respectively. This problem arises because existing classifications were developed based on sedimentation methods. Although laser diffraction and sedimentation methods correlate with each other, they are based on different physical principles, and conversion models between methods have proven inadequate.
*Objective*: To develop a new soil texture classification specifically designed for the laser diffraction method that ensures reliable interpretation of measurement data.

*Materials and Methods*: The new classification uses soil mechanical behavior (plasticity limit, liquid limit, plasticity index) and field-determined texture classes as References standards. A crowdsourced collection of 3,131 soil samples was assembled, varying in sampling location, texture class, organic carbon content, and soil type. All samples were analyzed for particle size distribution by laser diffraction, plasticity and liquid limits, and texture class was determined by field methods (cord-and-ring method/Kachinsky and ball-and-ribbon method/FAO/USDA). New boundaries for silt and sand fractions were established specifically for laser diffraction measurements. A machine learning model was developed to predict liquid and plasticity limits based on particle size distribution parameters obtained from laser diffraction.

*Results*: New fraction boundaries for silt and sand were determined for the laser diffraction method. Based on these boundaries, classification principles were developed and content ranges for silt and sand fractions were identified for both FAO/USDA and Russian (Kachinsky) classification systems. The ML model successfully predicts rheological properties from laser diffraction parameters, confirming the physical validity of the proposed classification system.

*Conclusion*: The newly developed classification eliminates the methodological gap between traditional sedimentation-based standards and modern laser diffraction instrumentation. It enables accurate interpretation of laser diffraction data within both international and national classification frameworks, promotes standardization of soil diagnostic studies, and can be integrated into digital soil mapping and precision agriculture protocols.

**Acknowledgments**
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# Revisiting soil water retention behavior as influenced by microbial growth under unsaturated conditions

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**ABSTRACT**

Bacterial biofilms play a crucial role in microbial survival during drought by modifying soil-water relations, yet their influence on water vapor transport in dry soils remains unexplored. We present the first systematic investigation of biofilm effects on soil water vapor sorption (SWVS) dynamics across a wide matric potential range (-400 MPa to -10 MPa). Using five soils of varying textures inoculated with Pseudomonas putida and Bacillus subtilis, we quantified SWVS isotherms while characterizing concomitant changes in surface and biofilm development. Key findings reveal that active biofilms persist in dry soils (water activity: aw < 0.9), fundamentally altering SWVS behavior through three mechanisms: (1) Enhanced water vapor adsorption capacity (10-49% increase across textures) due to extracellular polymeric substance (EPS) hydration; (2) Hysteresis reversal at critical aw values < 0.6, where biofilm-dominated adsorption exceeds mineral surface desorption; and (3) Displacement of mineral-water interactions by biofilm hydration. Mechanistic analysis demonstrates that EPS components dominate vapor sorption through high-density polar functional groups (-COOH and -OH) with strong water-binding affinity, polymer matrix swelling that physically obscures mineral surfaces, and competitive inhibition of cation hydration shells at particle interfaces. These findings establish biofilms as independent regulators of soil hydrology in dry conditions, with implications for microbial drought resilience strategies, soil water retention models in arid ecosystems, and biofilm-mediated contaminant transport. The study provides a framework to predict vapor-phase water redistribution in biofilm-colonized soils, filling a critical gap in the understanding of biological controls on soil hydraulic processes.

# Optimizing implementation strategies for efficient soil water evaporation measurements with multi-probe heat pulse sensors

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**ABSTRACT**

A multi-probe heat pulse (HP) sensor measures in-depth variations of water evaporation rates ($E$) in subsurface soil layers. A multi-probe HP sensor requires an input source of heating power, a high-frequency data logging system, and computer software for data analysis, which may hinder its adoption for a wide use in field applications. This study aims to optimize the measurement configurations via systematic evaluations of vertical probe distributions, heater probe requirements, and thermal property sampling intervals. Field data obtained with an 11-probe HP sensor revealed that 87% of evaporation occurred within the 0-23 mm soil layer during drying cycles, requiring the use of only seven temperature probes and two heater probes ($RMSE$ < 0.02 mm $h^{-1}$ vs. full configuration). Thermal property measurement intervals could be extended from 4 to 8 hours when timed to capture critical daytime transitions in soil thermal conductivity, maintaining accuracy while reducing the data collection requirement by 38%. Soil thermal gradients accounted for > 90% of sensible heat flux values, it was essential to maintain millimeter-scale precision on the depth placement of the topmost probes. These quantified operational thresholds provide sensor manufacturers and field researchers with evidence-based design criteria that balance measurement integrity and system efficiency.

**Acknowledgments**

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# Root-soil interface traits in modern and landrace barley genotypes differ in the lab but not the field

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**ABSTRACT**

Having been domesticated 10,000 years ago, barley is one of the oldest cereal crops and the fourth most grown in the world. Historic landraces are reported to have adaptations to nutrient and water use efficiency, and possibly a greater capacity to modify rhizosphere physical structure through root-soil interface traits but it is unknown if these have been 'bred out' in modern cultivars. Within Scotland, the "Bere" barley landrace is a multipurpose crop with cultural importance and evidence of advantageous root-soil adaptations to micronutrient deficiency.

We investigated the genetic potential of early seeding Bere genotypes under controlled conditions and found that they had up to 32 % larger total and specific rhizosheath (g/cm) than an elite cultivar KWS Curtis ($p<0.001$) despite having similar root lengths. Subsequent field validation with KWS Curtis and the largest rhizosheath forming Bere genotype "Unst" was conducted in two different Scottish Cambisols during the 2025 growing season- the driest in 30 years.

The most profound effect of these suboptimal conditions was in the above ground portion of the plant: mature plants grown in sandy loam soil had 4 times greater yield and 1.7 times greater above ground biomass than plants grown in loam soil ($p< 0.001$) and showed no significant difference in fresh root or total rhizosheath mass. Additionally, the root architecture of field grown plants were highly branched and showed diversity in root diameter when compared with controlled grown plants. This is expected to influence specific rhizosheath to a greater extent than total rhizosheath which is currently being evaluated. In the field at seedling stage, the total rhizosheath was less than half the size as under controlled conditions. Additionally, rhizosheath size in the field varied considerably with time and was more difficult to collect when soil moisture approached the wilting point. Ongoing work is exploring the 3D pore structure of the rhizosheath in the field using X-Ray CT imaging.

In spring 2026, the field study will be repeated and coupled with more in-depth measurements of root-soil interface properties to gain further understanding of Bere rhizosheath formation under varying field conditions.

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# Seasonal dynamics of soil structure and water retention of field soils with different long-term amendment rates of slurry and compost: measurements and modelling

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**ABSTRACT**

Over times as short as hours after tillage, soil structure and water retention characteristics can vary markedly, with longer-term impacts dependent on the form and quantity of organic inputs. While many studies have observed seasonal soil structure shifts due to organic amendments and cultivation, little data exists on water retention characteristics due to the time and expense required. In this study we apply a new inferred Assouline model that can infer soil water retention characteristics at different time points based only on simpler measurements of saturated water content, bulk density and macroporosity. We apply it to a field experiment exploring long-term field applications of 0, 10, 20 and 40 Mg ha$^{-1}$ slurry and 0, 35, 100 and 200 Mg ha$^{-1}$ compost (by fresh weight). Measurements were taken at post-planting and post-harvest across two years. Increasing amendment rates raised soil organic carbon (SOC) by 15 g kg$^{-1}$ in the highest slurry treatment and by up to 47 g kg$^{-1}$ in the highest compost treatment compared with the control. Consequently, bulk density significantly decreased from 1.15 Mg m$^{-3}$ in the control to 0.96 Mg m$^{-3}$ in soils treated with 200 Mg ha$^{-1}$ compost, while saturated water content followed the opposite trend. The form rather than the amount of SOC affected total porosity, which was significantly greater ($p \leq 0.05$) in compost-treated soils than in slurry-treated soils in both seasons, when the organic amendments were assessed at equivalent SOC content. There were variable effects of amendment type and time on soil structural and hydrological properties, but crop growth over the season helped regenerate soil structure and add new carbon, particularly in compost-treated soils, where microporosity and saturated water content increased post-harvest. From water retention characteristics assessed with the Assouline model, the scaling parameter related to drainage decreased from post-tillage (mean of 25 kPa for both amendments) to post-harvest (18 and 16 kPa in slurry- and compost-treated soils, respectively). Soil organic carbon also regulated drainage at more negative matric potentials, as reflected by lower exponential decline parameters at post-harvest (0.32-0.35) compared with post-planting (0.37-0.40). The scaling and exponential parameters were similar across treatments, suggesting a stronger influence of texture and soil management than of SOC content. Interaction effects between season and compost rate altered saturated water content and permanent wilting point, with decreases at post-tillage but increases at post-harvest. The new inferred Assouline model performed well, with 86 % of estimated soil water retention curves showing RMSE ≤ 0.05 m$^3$ m$^{-3}$ and an average $R^2$ of 0.96. Overall, maintaining high SOC through long-term organic amendments enhances pore stability, improves water retention, and supports soil health and productivity.

**Keywords:** Soil structure, slurry and compost, soil hydrological functions, water retention curve, inferred model.

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# Modelling the relationship between naturally occurring radionuclides and grain size of sediment of various river basins, South Africa

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**ABSTRACT**

This study examines the relationship between sediment grain size and naturally occurring radionuclide concentrations ($^{40}$K, $^{238}$U, $^{232}$Th) in the Helskloof Basin, South Africa. Sediment samples from the Klein Helskloof Valley were sieved into grain size fractions and analyzed by gamma spectroscopy using a 3×3 NaI(Tl) detector. Results show that $^{232}$Th concentrations consistently exceed $^{238}$U, while $^{40}$K correlates strongly with grain size and lithology, particularly in granodioritic areas rich in potassium-bearing minerals. Fitted activity–grain size relationships revealed a consistent minimum radionuclide activity between 612–678 µm (coarse sand), reflecting the dominance of low-radioactivity minerals such as quartz and feldspar. Similar studies in the Mkomazi and Tugela rivers, which differ markedly in lithology and climatic conditions, have shown that both geology and climate influence the relationship between grain size and radionuclide concentrations. These findings confirm that radionuclide distribution is controlled by lithology, climate, and sedimentary sorting, demonstrating the usefulness of natural radionuclides as tracers of sediment provenance and depositional processes.

# Construction of the Integrated Soil Database for Hydrological Modeling in Brazil

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**ABSTRACT**

Hydrological modeling is an essential tool to support decision-making, with wide application in soil management and conservation studies, water resource management, and environmental impact assessment. Among the most widely used models is SWAT (Soil & Water Assessment Tool), which requires soil parameters such as saturated hydraulic conductivity, textural fractions, density, and depth to simulate soil-water interactions. For developing countries, the scarcity of reliable and adequately organized input data increases the uncertainties associated with hydrological simulations. Currently, there are three main alternatives for obtaining soil data for models: global databases, which are comprehensive but have low resolution; observed data, which are accurate but expensive and time-consuming; and open access databases, which balance quality and availability. This last option requires estimating missing data and organizing them into the model format using pedotransfer functions (PTFs). Processing and formatting demand time and technical knowledge of soils. Considering the demand from the modeling community, this study aimed to develop an Integrated Soil Database for Hydrological Modeling in Brazil, with reliable and open information compatible with the SWAT and SWAT+ models. To achieve this objective, the methodology consisted of: I - Defining the parameters and organizing the input data necessary for the SWAT model. II - Establishing a minimum set of attributes that each soil profile should contain to allow the estimation of other parameters using Profile Transfer Functions (PTFs). III - Obtaining comprehensive and reliable soil databases. For the current version of the database, we used three main sources: the Brazilian Hydrophysical Soil Database - HYBRAS, the Brazilian Free Soil Data Repository - FEBR, and the Soil Database of the Brazilian Agricultural Research Corporation (EMBRAPA). IV - Standardization, concatenation, and cleaning of data. V - Estimation of missing parameters through the application of PReferences Transfer Functions (PTFs) chosen based on the availability and suitability of predictors for Brazilian soils. This process estimated the hydraulic conductivity in saturated soil, soil density, available water content, USLE-K factor, and albedo. As a result, the Integrated Soil Database for Hydrological Modeling in Brazil was generated, containing 7,944 soil profiles distributed throughout the country. The database includes the parameters required by the models, in a ready-to-use format. The resulting database expands the potential and reduces the time and effort required for the application of the models in Brazil.

**Acknowledgments**

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# Accurate soil thermal conductivity schemes are crucial for improved earth system modelling skill

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**ABSTRACT**

The gap between earth system or climate model simulations and observations is still a topic of scientific and political concern. The latest phase of the Coupled Model Intercomparison Project (CMIP) is still showing overestimations in near-surface air temperature among other parameters, despite various model structural improvements and numerical advances. Great efforts have been made to increase model skill, yet few studies considered the heat transfer within soil and at the land-atmosphere interface, which are dominated by soil thermal conductivity (STC) parameterization schemes (PS). By incorporating the commonly used STC-PS of various mainstream land surface models (LSMs) of earth system and climate models into the Community Earth System Model (CESM) and comparing with European Center Reanalysis version 5 (ERA5) and FLUXNET data, we found that the role of STC-PS in earth system model has been underestimated. The results unveil that STC-PS alone can lead to errors in global mean absolute bias (MAB) of shallow soil temperature of 2.1 °C with a 5~95% range of 1.75~3.26 °C. These errors propagate via the land-atmosphere interactions and feedbacks in earth system models, leading to MAB for near-surface air temperature of 1.67 °C with a 5~95% range of 1.53~2.07, and for sensible and latent heat flux of 9.8 W $m^{-2}$ with a 5~95% range of 7.8~12.4 W $m^{-2}$. Therefore, uncertainties arisen from STC-PS to a considerable extent explain the overestimated global mean temperatures and affect the decision-making processes concerning the global temperature rise targets. Hence, there is an urgent need to improve the neglected STC-PS to better understand our earth system, how it is affected by climate change and to guide our decisions on the best climate change mitigation strategies.

**Keywords:** Earth system models; land surface models; soil thermal properties; water and heat transport; FLUXNET

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# Applicability and transferability of the state-space approach to predict saturated soil hydraulic conductivity at watershed scale

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## ABSTRACT

Saturated soil hydraulic conductivity (Ksat) is a key factor in hydrological management projects and its variability along the landscape hinders its correct use in the formulation of such projects. Ksat varies under different climatic and hydrological conditions at spatial scales as reported in several studies. However, the applicability of the state-space approach to predict saturated soil hydraulic conductivity to other soils that do not belong to the data pool used to generate them remains a challenging aspect with regard to identifying supportive co-variates and suitable spatial models. The objectives of this study were to (i) describe the spatial continuum of Ksat across a 25 km-spatial transect established in the Pelotas River Watershed (BHAP) (Fig. 1), Southern Brazil, through co-regionalization with an autoregressive state-space model, (ii) evaluate its applicability to predict Ksat data along a 15 km-spatial transect established in the Fragata River Watershed (BHAF) as well as to predict Ksat data on a sampling grid of 106 sampling points spaced 50 m by 75 m established in a headwater sub-basin (BHSE) of the Pelotas River Watershed. One hundred soil sampling points were distributed along the 25 km-spatial transect at equal distances (250 m) where Ksat, Clay and Sand contents and soil bulk density (BD) were determined for the 0-20 cm layer at each point. The same data sets were determined in the BHAF and BHSE watersheds. Mean, standard deviation, maximum and minimum values were calculated for each data set. A lognormal transformation was applied to Ksat data set since that did not show normality. The Spearman rank correlation coefficient, autocorrelation and crosscorrelation functions were calculated to evaluate the spatial relationships between Ksat and the other three variables. A state-space model was run to assess the spatial relationships between Ksat and Clay and Sand and BD data sets in the 25 km-spatial transect where 92.37 % of the local variations of Ksat were explained by those of Clay, Sand and BD data sets. The variance parity test of Levene was applied between each data set of Ksat, Clay and Sand fractions in order to verify the homogeneity of variance. Results show that the BHAP-state-space model captured the local variations of Ksat in the BHAF and in the BHSE showing its potential to predict Ksat of basins with scarce data and similar soil and land-use conditions.

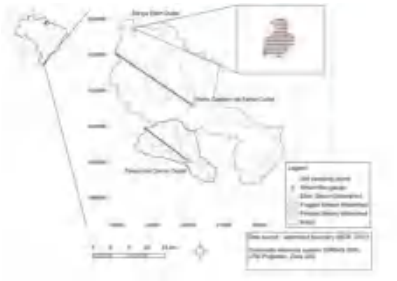


Fig. 1: Brazil's map and Southern Brazilian watersheds study.

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# Cover Crops, More Than Crop Rotation Diversity, Improve Soil Porosity, Carbon Storage, and Hydraulic Conductivity in a Long-Term No-Till Field Experiment in South Dakota

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## ABSTRACT

No-till management is widely practiced in South Dakota, but cropping systems are increasingly dominated by simple corn (*Zea mays* L.)-soybean [*Glycine max* L. (*Merr*.)] rotations, reducing crop diversity. We conducted this study to determine how declining crop diversity affects soil porosity, hydro-physical properties, and carbon storage in a long-term no-till field experiment with two crop rotations initiated in 1991. The experiment used a split-plot design in which a four-year corn–soybean–oat (*Avena sativa* L.)-rye (*Secale cereale* L.) rotation and a two-year corn–soybean rotation formed the main plots. Cover crop (CC) and no cover crop (NCC) treatments were implemented as split plots in 2013. Intact soil cores were collected at 10-cm intervals from 0 to 40 cm in 2022 and analyzed using X-ray computed tomography to quantify macropore characteristics, and hydro-physical properties were measured in the laboratory. The diversified four-year rotation increased macropore counts and density by 27% and 28%, respectively, compared with the two-year rotation at 0-10 cm. However, cover cropping exerted a stronger influence, increasing macroporosity and macropore counts by at least 30% and total porosity by 9% compared with NCC at 0-10 cm depth. In addition, CC treatments elevated soil organic carbon and total nitrogen concentrations at 0-10 cm and enhanced saturated hydraulic conductivity by 42-75% from 0 to 30 cm depth. These findings indicate that cover crops play a larger role than rotation diversity in improving soil porosity, carbon storage, and hydraulic conductivity within this long-term no-till field. Integrating cover crops into no-till management, therefore, represents a key strategy for building soil function and supporting more resilient cropping systems in South Dakota.

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# Impact of Dry-wet Cycles on Nitrogen and Phosphorus Mineralization in Soils Amended with Cattle Manure

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## ABSTRACT

Dry-wet cycles (DWCs), defined as alternating periods of dry and wet conditions in the soil, are predicted to occur more frequently worldwide due to the current change in global climate. These fluctuations in soil moisture conditions can affect soil structure and hydraulic properties, which can have a direct effect on biogeochemical processes such as mineralization. However, limited studies have examined how changes in soil physical and hydraulic properties during DWCs influence soil nutrient mineralization. The objective of this laboratory study was to characterize the impact of DWCs on nitrogen (N) and phosphorus (P) mineralization from two soils (a silty loam and a clay loam) amended with cattle manure. We also explored correlations between mineralization and field capacity (FC), permanent wilting point (PWP) and available water content (AWC) measured from a separate experiment investigating the impacts of DWCs on water retention parameters. Soils were mixed with cattle manure at a rate of 150 kg N $ha^{-1}$, adjusted to 60% of FC, and incubated at 30°C under three DWCs treatments (4, 8, and 12 DWCs). Each DWC consisted of a 2-day dry period followed by a 1-day wet period. A control treatment, not subjected to DWCs, was included for comparison. The experiment was arranged in a completely randomized design with all treatments replicated four times. After 36 days of DWCs, samples were maintained at 60% of FC for an additional 28 days, resulting in a total incubation period of 64 days. At the end of the incubation, available N (2 M KCl extractable $NH_4^+$ + $NO_3^-$) and P (Bray) were determined, and net N mineralization ($N_{min}$) and net P mineralization ($P_{min}$) were calculated. Results showed a significant decrease in $N_{min}$ only after 12 DWCs (45.31 mg $kg^{-1}$) relative to the control (76.98 mg $kg^{-1}$) in the clay loam but not in the silty loam. Correlation analysis revealed a strong negative relationship between $N_{min}$ and water retention at FC ($r$ = -0.90, $p < 0.0001$), PWP ($r$ = -0.82, p = 0.0001) and AWC ($r$ = -0.81, p = 0.0001) in the clay loam. In the silty loam, the relationship between $N_{min}$ and water retention parameters was weak and insignificant. Net P mineralization was not significantly affected by DWCs but differed significantly between the two soils, with both soils showing negative values. $P_{min}$ in the silty loam (-27.06 mg $kg^{-1}$) was significantly lower than clay loam (-19.50 mg $kg^{-1}$). In the clay loam, $P_{min}$ showed no significant correlation with water retention parameters, whereas in the silty loam, $P_{min}$ was positively correlated with AWC. Our results suggest that the link between soil water retention parameters and N and P mineralization under DWCs is soil-dependent. This study provides insights into how shifts in hydraulic properties driven by DWCs can influence nutrient cycling under a changing climate.

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# Biochar Effects on Soil Hydrophysical and Chemical Properties: Texture and Particle Size Matter

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**ABSTRACT**

Climate change poses critical challenges to soil and crop systems, particularly through increased drought frequency. Biochar (BC), a carbon-rich byproduct of biomass pyrolysis, has been proposed as a nature-based solution to enhance soil climate resilience. However, the variability in BC effects across different soil types complicates the predictability of its potential impacts and economic viability. This study systematically investigates the effects of BC on the hydrophysical and chemical properties of soils with contrasting textures – sand (S), silt loam (SiL), and clay (C).

We selected hardwood-derived BC (pyrolyzed at 550 °C), sieved it into two particle size fractions (63–200 µm and <63 µm), and mixed them to produce three differently textured BC types (1/4, 1/1, 4/1) with particle sizes ranging from 2 to 200 µm. These BCs were mixed with the soils at application rates (ARs) of 0%, 1%, and 5% (w/w), resulting in 21 unique soil-biochar mixtures (SBMs) including controls. Key soil properties – including pH, electrical conductivity (EC), bulk density (BD), porosity (Φ), unsaturated and saturated hydraulic conductivity ($K_h$ and $K_S$), water retention characteristics (θ), and plant-available water (AW) – were quantified, following a 16-weeks incubation with an initial 15% (w/w) water addition at 18 °C and a subsequent air drying <45 °C.

Results revealed significantly improved AW and K in sand, enhanced KS, BD, and total porosity in silt loam, and moderately altered water availability and KS in clay. The effects were strongly influenced by both soil texture and BC particle size, with fine BCs at higher ARs generally producing the most pronounced effects. A consistent pattern in water retention and flow characteristics was observed in relation to the particle size distribution (PSD) of both soil and BC in the SBMs. Additionally, AR and particle sizes mattered most in orchestrating pore reconfigurations that increased mesoporosity in coarse and fine-textured soils. Moreover, pH increased substantially in BC-amended sand treatments, while changes in silt loam and clay were moderate to minimal, respectively.

This study underscores the necessity of texture-specific BC application strategies and supports BC's role as a viable tool for enhancing soil water regulation and resilience in agricultural systems. Further experiments with exhaustive input data will facilitate accurate predictability of soil-biochar interaction, improving our preparedness for soil-related climate change risks.

**Keywords:** biochar, particle size, hydraulic conductivity, water retention, pH

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# In-situ determining the dynamic of soil bulk density by using the combined soil moisture and thermal property sensors in a Vertisol and its relationship with waterlogging

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**ABSTRACT**

The Vertisol (Shajiang black soil) in China is mainly distributed in the southern part of the Huanghuai plain with an area of 4 × 106 hm$^2$. The poor soil physical properties during shrinkage-swelling greatly limit crop growth. This study was based on a long-term field experiment including no-tillage (NT), rotary tillage (RT), subsoiling (SS) and deep ploughing (DP). With combined commercial soil moisture and thermal property sensors, the dynamics of bulk density (ρb) in 0-10 cm and 10-20 cm layers under different tillage treatments were monitoring in situ. The ρb dynamics in the 0-20 cm in the NT and the 10-20 cm layer in RT treatment were mainly caused by shrink-swelling. However, the ρb dynamics in the 0-20 cm in the DP and the 0-10 cm layer in RT treatment were predominantly determined by soil subsidence first and then shrink-swelling. A two-stage equation for the relation between ρb and soil moisture was proposed. The soil subsidence and shrink-swelling stages accounted for 17.0%-24.0% and 19.0%-32.5% of the ρb variation over the year, respectively. The dynamic of the least limiting water range (LLWR) was then derived from the established pedotransfer functions and the ρb dynamic. Thus, the relationship between the waterlogging stress time and the antecedent soil water storage and rainfall was established. The threshold of rainfall leading to the waterlogging stress of more than 3 days in the 0-10 cm and 10-20 cm soil layer were 83.7-127.2 mm and 54.2-86.6 mm respectively. When the rainfall stress events exceed 2 times, the maize yield will decrease by more than 50%. Compared with the NT and RT treatments (83.7-93.2 mm and 54.2-64.7 mm), the soil under the DP treatment held more rainfall (127.2mm and 86.6mm), reducing the risk of waterlogging stress. This study provides new understanding the relation between dynamic of soil structure and waterlogging stress.

**Keywords:** Soil structure; Thermal-TDR; Verstiol;Waterlogging; Least limiting water range; Tillage practices

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# Soil structure versus soil life: Microbial resilience to compaction in contrasting soil types

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**ABSTRACT**

Soil structure, defined as *"spatial arrangement of solids and pores"* is a key regulator of processes responsible for critical soil functions. Pores of different sizes provide distinct habitats for microorganisms, influencing their activity. Soil compaction alters pore architecture, yet its effects on microbial communities remain poorly understood, particularly across soil types. We hypothesized that compaction-induced changes in pore structure would differentially affect microbial activity depending on soil organic carbon content and texture.

We conducted a microcosm experiment using two soils with contrasting properties. Hortic Chernozem (Aric), (silty clay loam, total organic carbon (TOC) is 3.82 ± 0.02 %) from the Kursk and Stagnic Retisol (Cutanic) (sandy loam, total organic C is 1.93±0.01 %) from Tver regions in Russia. Soil microcosms were assembled according to the average macroaggregate composition with and without plant residues (*Zea mays L.*) were then compacted under uniaxial compression up to effective bulk densities (BDeff) of 1.3; 1.4; 1.5; 1.7 g.cm-3. Microcosms of Chernozem and Retisol incubated for 22˚C during 70 and 245 days, respectively. Moisture content was maintained filling the soil pore space within the range 40–60%. During incubation soil, sampling took place for biological activity determination. Soil structure in microcosms was evaluated using X-ray computed tomography.

Total soil porosity reduced by 6-fold with an increase in BDeff from 1.3 to 1.7 g.cm-3 in Chernozem and by 4-fold in Retisol. Despite this structural deformation under soil compaction, the differences in microbiological activity were poorly pronounced. The microorganism's response manifested in just soil microbial respiration decrease and partly in extracellular enzyme activity (EEA) fall. We hypothesized that this phenomenon occurred due to the dominance of physical effects over biological responses in short term. With a 10% decrease in porosity the gas diffusion decreases up to 10 times. At the same time micropores (< 30 μm) volume, where a large proportion of microorganisms reside – remains unchanged or increases under external influences. Probably, labile components were consumed within the first several days while more stable fractions remain inaccessible. That is why the microbiological properties at 70 days were the same in Chernozem.

Our findings suggest that soil organic carbon content and texture mediate microbial resilience to compaction, with implications for predicting biological responses to agricultural traffic in different soil types. Carbon-rich loamy soils have a diverse and abundant microbial community and can provide a high buffering capacity to external influences while Retisol with a low TOC and a high content of sand cannot sustain this, particularly over extended periods.

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# Soil moisture, irrigation efficiency, and soil strength interactions under centre pivot irrigation

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**ABSTRACT**

Water security is increasingly recognized as a critical challenge for agriculture, particularly as irrigation expands into soils with limited infiltration and high susceptibility to waterlogging. Understanding how water moves through soil under centre pivot irrigation is essential for improving water use efficiency and ensuring sustainable food production. Efficient irrigation requires not only uniform water application but also effective soil infiltration and storage. This study integrates soil moisture sensing, application uniformity, runoff measurements, and soil penetration resistance to evaluate water movement and soil physical constraints under centre pivot irrigation in Tasmanian soils. Application uniformity assessed with catch cans was high (CU = 95%, DU = 92%), indicating that the system distributes water evenly. However, soil moisture data from Sentek Drill & Drop sensors reveal that most of the applied water remains confined to the upper 0–10 cm, with minimal increase at 15–30 cm and no detectable change below 45 cm. Runoff measurements ranged from 0 to 23 mm, with an average of 5.3 mm, confirming that a substantial portion of the applied water did not infiltrate. Dye tracer and wetting-footprint observations further showed lateral redistribution and surface flow even on gentle slopes. Soil strength measured with a Rimik CP-300 penetrometer frequently exceeded 2 MPa in the upper 15– 20 cm, the threshold commonly associated with restricted root growth and reduced infiltration. Areas with higher cone index coincided with shallower infiltration, faster surface saturation, and greater runoff, indicating that compaction is a key physical constraint limiting irrigation efficiency despite excellent application uniformity. Together, these measurements demonstrate the importance of evaluating not only irrigation system design but also soil physical conditions that control water entry, storage, and movement. This integrated approach provides a practical diagnostic tool for improving irrigation scheduling, soil management, and water productivity in pivot-irrigated systems.

**Keywords:** Soil moisture; irrigation efficiency; irrigation effectiveness; catch can uniformity; soil strength; penetration resistance; runoff; infiltration; centre pivot irrigation; soil physics.

**Acknowledgments**

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# Quantifying the Impact of Tractor Tire Pressure and Soil Management History on Soil Porosity and Void Morphology

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**ABSTRACT**

Soil compaction from machinery traffic degrades soil structure, limits water movement, and reduces agricultural productivity. This study evaluated how tractor tire inflation pressure, soil texture, and long-term management history influence void morphology and porosity using X-ray computed tomography (CT). Well-managed soils shaped by reduced tillage and cover cropping were compared with poorly-managed soils exposed to intensive tillage and frequent traffic. Clay-loam and sandy-loam soils were subjected to low tire inflation pressure traffic, high tire inflation pressure traffic, and non-traffic control treatments. Well-managed clay-loam soils showed greater porosity and more fine voids, whereas poorly-managed clay-loam soils exhibited reduced porosity and stronger sensitivity to compaction, particularly under high inflation pressure. In sandy-loam soils, poorly-managed soils had greater porosity than well-managed soils and showed little change regardless of tire inflation pressure traffic treatments. Horizontally oriented voids dominated across all treatments, while vertical and inclined voids varied with management and texture. Compaction effects were most pronounced at 15 cm depth, with limited structural change at 30 cm. X-ray CT detected subtle compaction-induced changes in pore size and void orientation that bulk density could not capture. Although tire inflation pressure significantly affected clay-loam structure, management history more consistently shaped void morphology and porosity across both soil types, highlighting the importance of long-term conservation practices in mitigating compaction.

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# Dry-wet cycles promote microbial interactions and horizontal gene transfer

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**ABSTRACT**

Microbial interactions are in the core of evolutionary and ecological processes in soil and other environments, including horizontal gene transfer mediated by conjugative pili,[1] quorum sensing,[2] and chemical signaling that shapes social behaviors.[3] Although studies have reported that heterogeneous environments often induces population segregation into distinct microhabitats for long-term coexistence,[4] structured environments such as soils commonly generate localized polymicrobial interaction hotspots.[5] These hotspots promote the spatial organization of bacterial communities and contribute to soil biogeochemical processes.[6] However, our understanding of the environmental factors controlling these interactions remains limited. Under most conditions, natural soils are unsaturated, where fragmented aqueous habitats undergo frequent dry–wet cycle hydration processes,[7] significantly influencing passive bacterial dispersal and subsequent microbial interactions based on direct contact and molecular exchange.[8] Here, we show that small-scale hydrodynamic processes mediated by dry–wet cycle can passively drive microbial dispersal within populations, promoting the exchange genetic materials. Through experiments, we demonstrate that hydration-driven hydrodynamics can balance fitness differences between competing populations by restricting the dispersal of motile bacteria and facilitating the expansion of non-motile bacteria. These processes passively drive two previously segregated populations remix at the expanding front, resulting in spatial hotspots of conjugation. This study highlights the key role of microscale hydrodynamics in mediating bacterial interactions and genetic exchange, emphasizing the ecological impact of dynamic hydration on microbial interactions within structured environments.

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# Long-term organic fertilizer substitution alleviates the surface soil compaction of a Vertisol by improving soil structure

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**ABSTRACT**

Inappropriate fertilization management has emerged as a major driver of soil compaction in arable systems, suppressing crop growth and jeopardizing the long-term sustainability of agriculture. However, the mechanisms underlying plough-layer compaction induced by fertilization remain unclear, and the extent to which different substitution ratios of organic fertilizer alleviate soil compaction is still insufficiently understood. Here, we examined fertilization regimes established in 2012 to assess the long-term impacts of organic fertilizer substitution (NPK, 20%, 60% and 100%OM) on the physical properties and compaction characteristics of the 0-15 cm surface horizon in the Vertisol. Relative to the unfertilized control (CK), exclusive organic fertilization (100% OM) significantly increased cation exchange capacity, soil organic carbon (SOC), and glomalin-related soil protein (GRSP), and improving aggregate stability and promoting the transition of 0.25-2 mm aggregates into macroaggregates (>2 mm). By contrast, sole mineral fertilization (NPK) elevated SOC but reduced CEC, GRSP, and macroaggregate content, while markedly lowering soil pH. Pore-structure analysis demonstrated that compaction in Vertisol is not restricted to superficial crust within the 0-20 mm layer but represents a structural transformation across the surface soil layer, with the uppermost horizon being most severely affected. Long-term, high organic fertilizer substitution enhanced total porosity, 100%OM showing 2.84-fold higher porosity than CK. Rainfall markedly reduced porosity in 100%OM by ~119.17%, whereas sustained low organic fertilizer substitution and NPK decreased it and induced conspicuous cracking after rainfall-drying cycles, reflecting unstable soil structure. SOC, CEC, and GRSP emerged as key regulators of compaction, exhibiting strong correlations with aggregate stability. Although excessive organic inputs may lead to localized salt accumulation, the incorporation of crop residues seems to alleviate this and improved structural resilience. Overall, our findings highlight the contrasting roles of different proportions organic fertilizer substitution in shaping soil structural dynamics, providing new insights into the mechanisms of plough-layer compaction and strategies for sustainable Vertisol management.

**Keywords:** Soil compaction, organic substitution, aggregate stability, soil pore structure, X-ray computed tomography

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# Causality analysis and prediction of soil saturated hydraulic conductivity by combining empirical modeling and machine learning techniques

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**ABSTRACT**

Soil saturated hydraulic conductivity (Ks), as a fundamental property governing the behavior of water in the soil environment, is important to agriculture, environmental quality, water resources management, and engineering practices. However, the intricate interplay between Ks and environmental factors leads to substantial variability, making direct measurement costly and challenging. To provide a cost-effective indirect method with regard to Ks estimation, we proposed a portable modeling framework combing partial least squares structural equation modeling and artificial neural network (PLS-SEM-ANN). The framework was applied to a mountainous watershed characterized by humid climate, steep topography, and diverse land use. This approach demonstrated that the PLS-SEM-ANN was efficient in Ks modeling with a prediction accuracy of more than 80% ($R^2$ of 0.989 and 0.862 for model training and validation), which is comparable to that of the conventional artificial neural network ($R^2$ of 0.993 and 0.843 for model training and validation). According to structural equation modeling, land use significantly affected Ks through direct ($\beta$=0.237, $p<0.05$) and indirect ($\beta$=0.263, $p<0.05$) pathways, and soil properties, especially soil particle composition, were the most direct factor affecting Ks ($\beta$=0.410, $p<0.01$), while topography had a lesser effect on Ks ($\beta$=-0.023, $p> 0.05$). However, Shapley additive explanations (SHAP) analyses of PLS-SEM-ANN revealed significant nonlinear effects of topography on Ks, especially slope (SHAP mean absolute value = 0.92). Moreover, threshold testing showed that there was an abrupt change in the slope-Ks relationship at approximately 21°, with the effect of slope on Ks turning from positive to negative. This study provides an approach with explainable and transparent modeling results for Ks.

**Keywords:** Saturated hydraulic conductivity; Structural equation modeling; Artificial neural network; Mountain watershed

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# Straw incorporation depth drives microbial carbon sequestration by remodeling physical habitat in Mollisols

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**ABSTRACT**

***Background*** The retention of soil organic carbon (SOC) is inextricably linked to microbial metabolic activities within their physical microenvironments. However, the "physical-biological" coupling mechanism by which deep straw incorporation—a key management practice—drives carbon sequestration remains poorly understood.

***Methods*** Based on a 15-year field experiment in Mollisols, we compared three treatments: conventional tillage (CT), shallow straw incorporation (SS, 0–20 cm), and deep straw incorporation (DS, 0–35 cm).

***Results*** Result showed that SIT effectively constructed a favorable physical habitat in the subsoil (20–35 cm), significantly increasing macropore (>75 μm) volume by **42.4%** and enhancing pore connectivity by **2.5 times**. This structural improvement facilitated water infiltration; stable water isotope analysis ($\delta^2H$, $\delta^{18}O$) revealed a **16.3%** increase in the contribution of "new water" in the subsoil, while the mean residence time (MRT) of water was prolonged by **24%** compared to SS. By remodeling the physical environment, DS alleviated microbial resource limitations, enriched microbial taxa, and elevated their genetic potential for decomposing complex polymers (e.g., cellulose/lignin-degrading CAZyme genes increased by **45.8%**). Consequently, enhanced microbial activity promoted the accumulation of microbial-derived carbon, raising the contribution of fungal necromass to mineral-associated organic carbon (MAOM) to **58.2%**, and increasing total subsoil MAOM stocks by **30.5%** compared to CT.

***Conclusion*** This study confirms that deep straw incorporation promotes soil carbon sequestration potential by remodeling the physical habitat to drive a fungal-mediated microbial carbon pump, providing a mechanistic basis for optimizing straw management to enhance soil carbon storage.

# Estimation of soil water retention curves by combining thermal conductivity and electrical conductivity curves

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**ABSTRACT**

Soil water retention curve (SWRC), which describes the relationship between soil pressure head (*h*) and water content (θ), is fundamental for modeling water flow and solute transport in vadose zone hydrology. However, accurate estimation of SWRC across the entire θ range remains a challenge due to limitations in direct measurement methods and the constrained applicability of existing indirect models. Previous studies have independently explored the use of soil thermal conductivity (λ) or electrical conductivity (σ) for SWRC estimation, but these approaches are typically effective only within limited θ ranges. We hypothesized that λ and σ provide complementary information for estimating the soil water retention curve due to different pore-water regimes. Our investigation, conducted across a range of soil textural classes, confirmed that λ is the dominant parameter in dry to moderately wet conditions, owing to the formation of solid-liquid thermal pathways. In contrast, σ becomes more effective in wet conditions due to a sharp increase in ionic conduction through continuous liquid pathways.

Leveraging these complementary contributions and analogous conduction mechanisms, we developed a novel, two-segment pedotransfer function to estimate the SWRC across the full θ range using both λ and σ curves. Validation against independent laboratory datasets with simultaneous measurements of SWRC, λ, and σ demonstrated that the integrated model significantly improves estimation accuracy, reducing the root mean square error (RMSE) by over 20% compared to single-property models. This approach provides a more reliable and practical method for characterizing soil hydraulic properties across diverse moisture conditions.

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# The added value of CoreVESS score, penetration resistance, and geophysical techniques in predicting and characterizing the soil–water retention curve

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**ABSTRACT**

Soil hydraulic properties, such as the soil–water retention curve (SWRC), play a crucial role in simulating water transport within the vadose zone. They can be directly measured in the laboratory or field, or indirectly predicted by using Pedotransfer Functions (PTFs). It has been advocated that accounting for soil structure could marginally improve the prediction accuracy of PTFs in its wet range. This study evaluated whether integrating easy-to-determine soil structure variables, specifically a visual soil assessment score (Sq from CoreVESS) and penetration resistance (PR), could improve PTF accuracy. We analyzed 252 soil horizons from 42 crop fields exhibiting varying soil structural degradation. We compared classical regression and machine learning (e.g. k-Nearest Neighbors, KNN) approaches to develop both point and parametric (Van Genuchten) PTFs. To evaluate the effect of data grouping, the dataset was split in two based on structure and on texture. Overall, KNN-PTFs achieved the best performance showing the highest $R^2$ and lowest RMSE values. Moreover, the point PTFs showed much better and more stable predictive ability than parametric PTFs. The inclusion of PR as an additional predictor variable slightly improved the prediction performance in the wet range of the SWRC. Interestingly, Sq proved beneficial when substituted for bulk density but not when used in addition to it. Grouping data based on texture and structure improved the prediction accuracy of the PTFs, but not in KNN-PTFs.

Extending these point-scale findings, our current research focuses on upscaling assessment to a field scale. We aim to outperform current methods by integrating traditional soil sampling with semi-quantitative visual assessment techniques and non-invasive geophysical prospecting. More specifically, we explore the potential of methods such as electromagnetic induction, ground penetrating radar, seismic methods and electrical resistivity tomography to better understand it at different depths. In this way, complex soil hydraulic properties can be characterized at field scale using practical, non-invasive in-situ measurements.

# Hydrodynamic Shear Stress Regulates P. aeruginosa Attachment via Motility Organelles

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**ABSTRACT**

Soil biofilms participate in the biogeochemical cycles of most elements. While the formation of mature biofilms is well documented, the impact of hydrodynamic conditions, particularly fluid shear stress, on the early stages of biofilm formation (attachment and colonization) remains largely underexplored. This study investigated the micro-mechanism of *Pseudomonas aeruginosa* (PAO1) biofilm formation under shear stress from a biophysical perspective.

Using a flow culture system established with microfluidic chips and injection pumps, we examined the attachment behaviors of Ancestral PAO1 and its two motility mutants: flagella-deficient (Δ*fliC*) and type IV pili-deficient (Δ*pilA*). Biofilm development was monitored using Confocal Laser Scanning Microscopy (CLSM) and analyzed alongside theoretical modeling.

The results demonstrated distinct responses to varying shear stresses. At a low shear stress of 0.25 dyn/cm², the presence of flagella significantly influenced bacterial distribution and quantity. Both Ancestral PAO1 and Δ*pilA* strains developed complex "mushroom-shaped" biofilm structures, whereas the Δ*fliC* mutant did not, indicating that flagella play a critical role in the architectural development of biofilms.

Under a moderate shear stress of 0.6 dyn/cm², the attachment ability was ranked as: Δ*pilA* > Δ*fliC* > Ancestral PAO1. While type IV pili facilitate initial surface anchoring, their associated twitching motility, combined with flagellar swimming enhanced near-surface motility, which was unfavorable for stable attachment under these flow conditions. Furthermore, under shear stress, PAO1 strains possessing type IV pili exhibited a tendency to crawl along the flow direction.

At high shear stress of 6 dyn/cm², physical forces dominated over biological mechanisms. The increased drag force prevented cellular aggregation and 3D structure formation, resulting in a dispersed, monolayer distribution for all strains.

In conclusion, fluid shear stress significantly dictates the spatial structure and attachment dynamics of *P. aeruginosa* biofilms. The interplay between shear forces and bacterial motility organelles (flagella and type IV pili) is a key determinant in the early-stage colonization of surfaces.

# Root-mediated regulation of soil infiltration dynamics in eroded Mollisols

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**ABSTRACT**

Water infiltration is a fundamental hydrological process in terrestrial ecosystems, influencing surface runoff, soil erosion, plant growth, and groundwater recharge. Although vegetation restoration is widely recognized for improving soil infiltration, how root-soil interactions respond to erosion-induced changes in soil profile stratification and related properties, and how these responses affect the hydrological effectiveness of vegetation restoration, remain poorly understood. In this study, we simulated the topsoil loss due to erosion by constructing soil columns with varying thicknesses of the black soil layers (30 cm, 20 cm, 10 cm, and 0 cm), representing a stage of no erosion, mild erosion, moderate erosion, and severe erosion. This gradient was achieved by layering different proportions of surface black soil and underlying depositional subsoil. We then compared soil infiltration rates and patterns across the erosion gradient under bare soil conditions and with four perennial herbaceous species: two Poaceae (*Festuca arundinacea* and *Bromus inermis*) and two Fabaceae (*Medicago sativa* L. and *Astragalus adsurgens*). Results showed that in the absence of vegetation, intensified black soil erosion reduced infiltration rates by more than 60% and shifted infiltration patterns from matrix flow to localized preferential flow. Notably, these preferential flow paths, initiated by unstable cracks, were transient and contributed minimally to overall infiltration. Meanwhile, vertical water infiltration was restricted, while near-surface lateral flow was enhanced, particularly under moderate erosion (10 cm black soil layer), where the effect was most pronounced. The effects of different herbaceous species on infiltration rates and water flow behavior varied depending on root morphology and erosion severity. Fabaceae species, with their well-developed taproot-lateral root systems, consistently increased infiltration rates by13.36%–90.91% across all erosion levels, promoted deep water infiltration and recharge (maximum stained depth increased by > 60%), suppressed lateral flow (stained width-to-depth ratio decreased by > 30%), and significantly enhanced the development of stable preferential flow (preferential flow fraction increased by > 100%) under moderate and severe conditions. In contrast, Poaceae species, characterized by fibrous root systems, improved infiltration rates and promoted preferential flow only in non-eroded and mildly eroded soils, but their effectiveness was generally lower than that of Fabaceae. This study highlights the importance of matching plant types to erosion severity when designing vegetation-based restoration strategies for degraded black soils. Such matching is critical for effectively restoring infiltration capacity and hydrological function. These findings provide valuable insights for developing targeted soil hydrological restoration and water resource management strategies in Mollisols and other regions with similar soil profiles and climatic conditions.

**Keyword:**Infiltration rate; Preferential flow; Soil profile stratification; Root system architecture; Fabaceae; Poaceae

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# Controls on near-saturation water retention and structural stability of soils across four climatic regions: long-term land use versus single amendment

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**ABSTRACT**

Enhancing soil structure is fundamental to sustaining soil functions and overall soil health, and its development is strongly governed by climate, land use, and soil type. This study evaluated near-saturation water retention as an indicator of soil structural condition across four climatic regions under long-term land use and compared these effects with a single application of an anionic polyacrylamide (PAM).Soils were collected from humid (USA: crop conventional tillage, CT; crop no-till, NT; grass; forest), temperate (Ethiopia: crop CT; grass; bush; forest), semi-arid (Turkey: crop CT; grass; forest), and arid (Israel: crop CT; orchard; virgin) regions, comprising 272 samples with textures ranging from sandy loam to clay. In each region, three crop CT soils with contrasting textures were treated with PAM at 0, 25, 50, 100, & 200 mg $L^{-1}$ (60 samples). Structural responses were quantified using the high-energy moisture characteristic (HEMC, 0–50 hPa). Water-retention curves were described using modified van Genuchten parameters (α and n), and soil structural stability was expressed as a stability index (SI). Treatments produced distinct curve shapes (α = 0.036–0.099 $hPa^{-1}$; $n$ = 7.1–20.6), reflecting shifts in macropore domains (>250, 125–250, and 60–125 µm) associated with large- and small-macroaggregate stability (SI = 0.002–0.060 $hPa^{-1}$).Higher soil organic carbon (SOC; crop CT < crop NT < grass/bush/orchard < forest/virgin) and increasing PAM rates increased α (0.054–0.096 $hPa^{-1}$) and SI (0.004–0.059 $hPa^{-1}$), while decreasing $n$ (16.0–6.3). The magnitude of these responses depended on soil texture, soil type, and climatic region. SI correlated strongly with SOC or the SOC/clay ratio in humid and temperate regions, and with SOC and clay content in semi-arid and arid regions. Crop CT soils exhibited the lowest SI, typically 2–4 times lower than other land-use types, whereas PAM application at 25–50 mg $L^{-1}$ increased SI (0.007–0.033 $hPa^{-1}$) to levels comparable with crop NT, grass, bush, or orchard soils (0.009–0.032 $hPa^{-1}$). Higher PAM rates (100–200 mg $L^{-1}$) further increased SI (0.014–0.042 $hPa^{-1}$), reaching values comparable to forest or virgin soils (0.014–0.059 $hPa^{-1}$), with strongest effects in medium- and clay-textured soils, and drier regions and, where PAM often exceeded SOC effects. Across all climates, long-term NT or grass soils with SOC ≥ 2 g $kg^{-1}$ and soils treated with 25 mg $L^{-1}$ PAM exhibited similar SI values, indicating a practical threshold for structural quality (SI ≥ 0.010–0.020 $hPa^{-1}$). Exponential relationships between SI and α or $n$ (α: $R^2$ = 0.85; $n$: $R^2$ = 0.64; $p < 0.001$) provide a quantitative basis for (i) assessing soil SI, and interpreting land-use effects on pore- and aggregate-size distributions; (ii) defining rational PAM rates in conservation agriculture, and (iv) the development of resilient soil structure, accelerated SOC accumulation, and site-specific management strategies, particularly for weakly structured and degraded soils.

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# An analytical solution for measuring thermal properties with heat pulse method under convective boundary conditions at the soil-atmosphere interface

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**ABSTRACT**

The Dual-Probe Heat-Pulse (DPHP) method, typically relying on the infinite line heat source model with adiabatic boundary conditions (ILS-ABC), is widely used to measure thermal properties at the soil–atmosphere interface. However, strong surface convection can induce significant errors in the ILS-ABC model, even for shallowly buried sensors. To address this, we developed a modified analytical solution incorporating convective boundary conditions (ILS-CBC) using the Green's function method to accurately determine thermal conductivity ($\lambda$) and heat capacity ($C$). The applicability of this new model for thermal property inversion was verified via finite element simulations and DPHP experiments. Theoretical analysis demonstrates that neglecting convective flow (i.e., using the ILS-ABC solution) causes errors in thermal conductivity to increase non-linearly with the convective heat transfer coefficient ($h$). For a sensor at a 1-mm depth, errors exceeded 20% when $h > 5$ W·m$^{-2}$·K$^{-1}$. The ILS-CBC method significantly improves measurement accuracy in the near-surface layer (0–5 mm) under strong convection ($h$ = 5–50 W·m$^{-2}$·K$^{-1}$). This solution offers a robust tool for studying surface energy balance and heat exchange processes at the soil–atmosphere interface.

# Variation in soil hydraulic properties under different land use in long term experimental plots across Canada

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**ABSTRACT**

The understanding of soil hydro-physical properties is critical in addressing the current issues in hydrogeology, plant growth, soil health and agricultural sustainable development. Soil hydraulic properties regulate water movement and nutrients transport and are significantly influenced by different land management practices (tillage/no tillage, crop rotation, residue management and fertilization regimes). Although there are extensive research on different soil management practices, a major gap still remains in understanding how long-term treatments interactively and persistently alter soil hydraulic properties. How stable is saturated hydraulic conductivity (Ks) and soil water retention curves （SWRC）after over decades continuous land management? How does long-term land use affect the recovery of soil hydraulic properties after disturbance? How soil hydraulic resilience response to modified soil structure, especially for compacted soil? To answer these proposed questions, soils under different treatments (Tillage system and crop rotations) with consistent management were collected from Canadian long-term research experimental plots. Topsoil (0-15 cm) and subsoil (15-30 cm) samples including intact soil cores and bulk soils were analyzed for soil hydraulic properties: Ks, SWRC ,bulk density, field capacity, permanent wilting point, total available water and pore-size distribution. Conventional pressure plates were used to measure SWRC and Permeameter apparatus was used to determine Ks. Classic Van Genuchten model was applied to estimate and fit the curves of SWRC. Visible and near-infrared (Vis-NIR) spectroscopy was used to rapidly predict the estimation of SWRC and provide comprehensive assessment on various soil properties. Results shows that long-term management practices significantly altered soil structure and hydraulic behavior with higher bulk density, higher total porosity, uneven pore size distribution and reduced saturated hydraulic conductivity. Bulk density in subsoil layer is higher than that in topsoil. Soil cores in subsoil layers were easier saturated than topsoil samples, indicating compacted soil formation from upper layers. These findings demonstrate that long term sustained management practices can lead to persistent changes in soil hydraulic properties, with negative implications for soil water availability, soil health and ecosystem resilience. The better understanding of the variation of soil hydraulic properties will provide suggestions to restore soil function, recover soil hydraulic properties and achieve long-term soil management goal.

**Keywords:** soil hydraulic properties, long-term treatments, soil structure, soil water retention curves, saturated hydraulic conductivity.

# Impacts of model root exudates (Pectin and Oxalic Acid) on multiscale soil structural, hydraulic, and surface properties

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**ABSTRACT**

Roots excrete mucilage and organic acids as rhizodeposits, which due to their distinct physicochemical properties have gelling and dispersion effects on soils. Along a growing root, these rhizodeposits will interact, but their combined impact on soil physico-chemical behaviour has received limited study. Here pectin simulated mucilage, and oxalic acid simulated organic acids, both identified in natural root exudates.

At the macroscale, soil core experiments were conducted under controlled water potentials and compression loads to assess changes in soil mechanical properties (compression characteristics, hardness, elasticity, and penetration resistance) and soil water properties (water content, sorptivity, and repellency); At the mesoscale, soil aggregate stability was determined via Le Bissonnais methods (fast wetting, slow wetting, and mechanical stirring) to elucidate stabilization mechanisms. At the microscale, soil surface properties (surface potential, charge density, specific surface area) and interparticle forces (electrostatic repulsion, hydration repulsion, van der Waals forces) were measured.

Macroscale results at 200 kPa compression (tractor wheel–like) and -50 kPa water potential showed pectin and pectin-oxalic acid mixed exerted the strongest mechanical effects. Pectin decreased soil hardness by 25.6%, increasing to 36.1% when combined with oxalic acid, whereas oxalic acid alone reduced hardness by only 13.9%. Penetration resistance showed a similar trend, with the mixed treatment decreasing penetration by 47.5%, compared to 32.4% for pectin alone. Pectin treatments also markedly enhanced soil water retention, consistent with hydrogel behaviour, whereas oxalic acid reduced water repellency under dry conditions, indicating a surfactant effect. These effects intensified with increasing compression and decreasing water potential., highlighting the role of rhizodeposits in alleviating drought- and compaction-induced stresses.

Mesoscale aggregate stability tests showed that under fast wetting conditions, pectin and pectin-oxalic acid mixtures improved aggregate stability by 62.5% and 67.18%, respectively, whereas oxalic acid alone slightly reduced stability and consistently decreased aggregate stability under slow wetting and mechanical stirring conditions. Microscale analyses showed that oxalic acid increased specific surface area without significantly altering surface charge number, resulting in a 6.8–12.1% reduction in soil surface potential and enhanced interparticle repulsion. These microscale changes explain the observed aggregate destabilization and weaker macroscopic structural improvements under oxalic acid treatment.

Overall, these results demonstrate that mucilage-dominated rhizodeposits stabilize soil structure across scales, whereas organic acids promote particle repulsion and structural destabilization, emphasizing the importance of rhizodeposit composition in regulating soil physical resilience.

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# Study on the Evolution of Multi-scale Pore Structure and Hydraulic Properties in the Arable Layer of Paddy Fields

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## ABSTRACT

Soil pores are critical in regulating water transmission within the arable layer of paddy fields, with their structure and characteristic parameters significantly influenced by the duration of rice cultivation. However, the multiscale evolution of pore structure and corresponding hydraulic properties in paddy fields with varying cultivation histories remains poorly understood. This study employed computed tomography (CT) scanning to systematically analyse the evolution of soil pore structure within the 0-15 cm plough layer at three scales: soil column (resolution > 240 μm), soil core (resolution > 50 μm), and soil aggregate (resolution > 6 μm). The investigation further integrated measurements of saturated hydraulic conductivity and soil moisture characteristic curves to explore the response of soil porosity to hydraulic properties.

Results indicate that with increasing years of rice cultivation, total porosity at both soil column and soil core scales decreased significantly, from 10.69% and 9.5% to 1.52% and 4.38% respectively. Conversely, the pore structure at the soil aggregate scale, primarily governed by root activity, exhibited no discernible temporal variation. Node density fluctuated downward with increasing cultivation duration at both soil column and soil core scales, while at the soil aggregate scale it initially increased before decreasing; The hydraulic radius progressively increased with tillage duration at the soil column scale (from 0.4053 mm to 1.9565 mm), exhibited an initial increase followed by a decrease at the soil core scale, and showed an initial decrease followed by an increase at the soil aggregate scale. Connectivity gradually decreased with tillage duration at the soil column scale, while both soil core and soil aggregate scales displayed an initial increase followed by a decrease. Fractal dimension, mean tortuosity, and length density showed no discernible trend with tillage duration. As the observation scale shifted from soil columns to aggregates, the proportion of biopores progressively increased while the proportion of non-biopores correspondingly decreased (Fig.1). Concurrently, node density, surface area density, and length density rapidly increased, whilst hydraulic radius gradually diminished. Pearson correlation analysis indicates that saturated hydraulic conductivity exhibits significant correlations with mean macropore volume (r = 0.90), average angle (r = 0.94), and surface area density (r = 0.89) at the soil core scale, while showing weaker correlations with pore characteristics at the soil column and soil aggregate scales. This study elucidates the evolutionary patterns of pore structures and multi-scale hydrological responses in paddy soil arable layers over cultivation timelines, providing theoretical References for soil structure improvement and irrigation management in rice paddies.

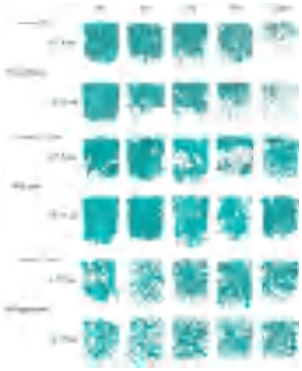


Fig.1 Three-dimensional pore images at different scales

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# Effect of organic matter on isothermal thermogravimetric profiles in the low temperature range (60°C–200°C)

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**ABSTRACT**

Knowledge about how organic matter affects isothermal thermogravimetric (TG) profiles of soils within the low temperature range (60 - 200°C), and about how these profiles relate to physicochemical properties, remains limited. In this study, isothermal TG profiles were measured for mixtures of three representative clay minerals with humic acid (HA) at different mixing ratios( 0%, 2%, 4%, 6%, and 8%), and for thirteen soils with different organic carbon contents(1.16% - 4.72%), before and after OC removal, within 60°C to 200°C. Except for pure kaolinite, which showed a linear increase in mass loss (ML) with temperature ($R^2 = 0.98$), all other samples exhibited a logarithmic increase in ML ($R^2 > 0.98$). For kaolinite, adding HA increased ML, with a more significant increase observed in the 60 - 105°C range compared to 105 - 200°C. For illite (IL), HA concentrations below 4% had little effect on the TG profile, while HA content above 6% significantly enhanced ML, particularly in the 105 - 200°C range. In contrast, HA had a minimal impact on the TG profile of montmorillonite (Mon). For most soil samples (11 out of 13), the presence of OC increased ML at different temperatures, with a more significant increase observed in the 60 - 105°C range compared to 105 - 200°C. Within 60 - 200°C, water content of all investigated samples decreased linearly with increasing pF (logarithm of negative water potential), and this relationship was well described by the Campbell and Shiozawa (1992) model ($R^2 > 0.96$). For KAO, the reciprocal of parameter SL, 1/SL showed a linear relationship with HA content ($R^2 = 0.94$), whereas for IL, 1/SL showed a quadratic relationship with HA content addition ($R^2 = 0.99$). For soils, the presence of OC reduced the explanatory power of the linear models built between 1/SL and CEC, $SSA_{N2}$, and $SSA_{H2O}$.

# How Water-Salt Stress Reshapes the Rhizosphere and Regulates Growth in Suaeda salsa

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**ABSTRACT**

*Suaeda salsa L.* is a halophyte in arid saline–alkali landscapes and a promising species for vegetation establishment. Rhizosphere responses, including soil physical shifts and exudate-driven microbial assembly, remain insufficiently quantified. Here we subjected *S. salsa* to four soil-water levels and four salinity levels (0–200 mM NaCl) and contrasted rhizosphere versus bulk soil properties. We quantified volumetric water content (VWC), penetration resistance (PR), electrical conductivity (EC) and pH, and integrated untargeted metabolomics with amplicon sequencing to resolve exudate profiles, inferred pathways and microbiome shifts. Moderate salinity (50–100 mM NaCl) increased shoot and root biomass and enhanced total root exudation. Across treatments, the rhizosphere exhibited higher PR than bulk soil, and the rhizosphere–bulk PR contrast increased with drought intensity. EC was lower in the rhizosphere than in bulk soil, whereas rhizosphere pH was higher. Redundancy analysis identified VWC, PR and pH as the dominant predictors of plant performance. Structural equation modelling showed that rhizosphere conditions, microbial diversity and core metabolites jointly explained 93% of the variation in plant growth, with total root length and pH exerting significant positive direct effects. Responses were threshold-dependent: from 0–100 mM NaCl, low salinity promoted root development and increased exudation, supporting growth; at ≥200 mM NaCl, plants enhanced salt–drought tolerance by downregulating the tricarboxylic acid cycle (lower energy demand) and enriching Proteobacteria and Bacteroidetes. These findings connect plant phenotype, exudate–microbe interactions and rhizosphere physical conditions, offering a soil-physical perspective on halophyte adaptation and guidance for restoration and rhizosphere management in arid saline–alkali lands.

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# Effects of long-term fertilization on soil macropore structure and hydraulic conductivity in paddy soils

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## ABSTRACT

Repeated flooding and drainage create wet–dry cycles that influence soil structure in paddy fields. Shrinkage cracking and connected macropores enhance preferential flow and increase deep percolation, whereas a pore system dominated by small pores promotes matrix flow with slower, more uniform infiltration. Therefore, pore structure and pore size distribution are important for water movement and drainage management in paddy soils. In recent years, X-ray computed tomography (X-ray CT) has been widely used as a rapid, non-destructive method to quantify soil pore structure in three dimensions. However, there are still few studies that link soil physical properties such as saturated hydraulic conductivity ($K_s$) in paddy soils to specific, quantitative structural parameters of the pore network. Furthermore, the long-term effects of organic fertilizer and soil amendment practices on paddy soil pore structure have rarely been directly observed. We hypothesize that long-term fertilizer management can reshape paddy soil pore structure and thereby change $K_s$, and we aim to use X-ray CT to identify the key pore-network parameters to explain saturated water flow.

Soil column samples (height: 5cm; 100 cm³) were collected from the paddy field in Fukushima, Japan, where four fertilizer managements were prolonged for more than 80 years: soil amendment (SA; NPK plus compost and soil ameliorants, i.e., silicate lime and fused phosphate), no chemical fertilizer (NF), mineral fertilizer (NPK), and compost (C). The column samples were collected at 2-7, 10-15, and 20-25 cm depths. Samples were equilibrated to a given matric potential targeting an equivalent pore diameter to standardize the macropore domain prior to scanning. Samples were imaged by X-ray micro-CT (voxel size 17.6 μm), and we quantified macropore volume and numbers, pore-size metrics (mean, minimum and maximum diameter), and pore network tortuosity. Finally, saturated hydraulic conductivity (*Ks*) was measured.

In the surface layer (2-7 cm depth), total macropore volume showed a clear tendency: SA was highest, followed by C, NPK and NF; SA was significantly higher than NF ($P < 0.05$). Fertilization affected soil pores not only in terms of volume but also in pore number. NF showed both smaller pore volume and fewer pore numbers. The effect of fertilizer management on $\log_{10}(K_s)$ was depth-dependent: treatment differences were clear between 2–7 and 10–15 cm. Across all samples, $\log_{10}(K_s)$ was positively correlated with total macropore volume ($r \approx 0.64$) and through-going macropore volume ($r \approx 0.47$), suggesting that permeability was governed primarily by the volumetric contribution of connected macropores rather than pore number.

Our results suggest that organic inputs and soil amendment (C and SA) tended to increase macropore volumes in the upper soil, enhance the complexity of the pore network and then affect hydraulic conductivity. However, the effect gradually weakened with increasing soil depth.

# Transformation of Agro-Physical Soil Properties During Urbanization: A Case Study in the Republic of Adygea

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**ABSTRACT**

Amid accelerating urbanization, soil serves as a key urban-ecosystem component, enabling carbon sequestration and water-air regimes for plant. Agro-physical properties: granulometric composition, bulk density, hydraulic conductivity directly influence green space quality. Land use changes trigger soil properties transformation, driven by urban-specific factors distinct from natural landscapes.

This study examines soil changes in recreation areas in comparison with background (undisturbed) areas.The purpose was to investigate the transformation of agro-physical soil properties during urbanization, using the Republic of Adygea as a case study. Key tasks included: landscape-ecological and functional zoning, field measurements of physical properties and laboratory analysis.

Study sites encompassed soils from Giaginsky and Maikop districts in Adygea, in two variants: central park areas of Giaginskaya and Dakhovskaya, and sites outside settlements. Besides the study was augmented by a Maikop city park site, where freshly imported lawn substrate and its properties after one year were assessed. Instruments included 101 $cm^3$ cylinders (Kachinsky method), micropenetrometer and 10 cm tubes for filtration coefficient. Granulometric composition was analyzed via laser diffraction on a Mastersizer 3000E with ultrasonic pre-treatment; solid phase density by pycnometry; and carbon content by dry combustion on an express analyzer.

Soils in Giaginsky are leached chernozems, with humus horizons exceeding 65 cm depth in both profiles. In the foothill Dakhovskaya gray forest soils are placed.

The most pronounced differences between urban and background soils occur in surface horizons. Bulk density in all variants is low despite heavy granulometry, similarly distributed in urbanized and background profiles: 0.99 $g/cm^3$ at surface, rising to 1.3 $g/cm^3$ at 30 cm depth. In Dakhovskaya park, the pattern reverses: 1.38 $g/cm^3$ at the upper layer and 1.14 $g/cm^3$ at 30 cm, possibly due to recreational loading. Penetration resistance <3 MPa, classifying these as well-structured soils. Exceptionally high and very high Eggerlsmann filtration rates prevail in upper horizons, declining to high and moderate values with depth. Urbanized soils exhibit slower water permeability than background ones.

At the Maikop site surveyed in 2024 and re-assessed in 2025, compaction changing from 1.2 to 1.3 $g/cm^3$, penetration resistance rising from 29.4 to 273.6 kPa, and filtration coefficient dropping from 42.5 to 19.3 cm/day. These shifts indicate gradual deterioration of water-air properties for plant growth. Nonetheless, values remain within optimal ranges, below critical limits.

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# Nitrous oxide emissions in Argiudolls of the Central Pampas Region of Argentina managed with no-tillage and controlled traffic farming

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**ABSTRACT**

In modern agriculture, soil compaction can increase nitrous oxide ($N_2O$) emissions by restricting the water movement, thereby promoting anaerobic conditions that favor denitrification. Controlled traffic farming (CTF) has the potential to mitigate $N_2O$ emissions by confining soil compaction to permanent traffic lanes (PTL). The aim of this study was to evaluate the effect of CTF systems, which use commercially available machinery, on soil $N_2O$ emissions. The study was conducted on two Typic Argiudolls located at Aurelia and Videla sites, in the central Pampas of Argentina. Measurements were carried out in both permanent traffic lanes (PTL) and permanent crop beds (PCB) within the on-farms experiments cultivated under no-tillage. Two treatments with three replications were established, corresponding to different levels of soil compaction applied to the PTL: T0, soil without additional traffic (historical compaction), and T1, soil subjected to additional compaction with a harvester combine until penetration resistance reached 4 MPa. Within each plot, two sampling positions were defined (PTL and PCB), resulting in a total of 12 sampling points. Soil water content, air and soil temperature, bulk density, nitrate concentration, and $N_2O$ fluxes were monitored over one month during autumn and summer. The results showed that $N_2O$ fluxes were influenced by water-filled pore space, soil temperature, and the initial level of compaction applied to the PTL. Emissions from PTL were significantly higher than those from PCB during autumn (Aurelia), whereas no significant differences were observed in summer (Videla). Cumulative $N_2O$ fluxes at the Aurelia site, were 240 (PTL-T1), 61 (PCB-T1), 158 (PTL-T0), and 51 (PCB-T0), all as g $N_2O$-N $ha^{-1}$. Cumulative emissions from PTL were significantly higher than those from PCB. At the Videla site, cumulative $N_2O$ fluxes were 22 in PTL-T1, 29 in PTL-T0, 18 in PCB-T1, and 20 g $N_2O$-N $ha^{-1}$ in PCB-T0, respectively. Cumulative $N_2O$ emissions at this site showed no differences between treatments or sampling position, and the overall average was 22.5 g $N_2O$-N $ha^{-1}$. Overall, the CTF system reduced soil $N_2O$ emissions by approximately 50% under wet soil conditions, even at low soil temperatures. In contrast, when water-filled pore space was low, $N_2O$ emissions remained close to background levels and were not affected by soil temperature.

**Key-words:** water-filled pore space, soil temperature, air temperature, soil bulk density, soil compaction

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# Bearing capacity of an Argiudoll under direct seeding and controlled machinery traffic amended with soluble calcium

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**ABSTRACT**

Machinery traffic is one of the main causes of soil compaction in Argentina. Soils with high silt content that have lost organic matter and binding cations such as $Ca^{+2}$ are susceptible to compaction. Replenishing binding cations is important to maintain the internal aggregates strength, but it is also essential not to exceed the soil bearing capacity, a value calculated from the compression curve and known as pre-compression pressure (σ). One alternative to avoid soil compaction is controlled machinery traffic (CMT), which is little used in Argentina. The objective of this study was to evaluate the effect of soluble calcium application on the soil bearing capacity of a typical Argiudoll located in Santa Fe (Argentina) cultivated under no-till and eight years of CMT use. 1,500 kg/ha of a calcium sulfate plus calcium hydroxide (70:30) amendment was applied to raise the $Ca^{+2}$ saturation of the cation exchange capacity to 70%. In plots, three compaction treatments were established in the permanent traffic lanes (PTL): PTL-T0 (control-no initial compaction), PTL-T1 and PTL-T2 (PTL initially compacted to reach 2 and 4 MPa of mechanical resistance, respectively), each one with their corresponding permanent crop bed (PCB) PCB-T0, PCB-T1, and PCB-T2. The calcium amendment was applied to half of the plots following a completely randomized block design with split plots and three replicates (n=18). Eight months after the $Ca^{+2}$ application, cylinders (7.5 cm diameter and 2.5 cm height) were collected from the center of each PTL and PCB at 0-10 cm, 10-20 cm, and 20-30 cm depth and equilibrated at 10 kPa of tension. Compression curves were obtained using an automated consolidometer and σ values were calculated. In the PCB, $Ca^{+2}$ application decreased σ: 54 vs. 68 kPa (0-10 cm), 112 vs. 149 kPa (10-20 cm), and 126 vs. 164 kPa (20-30 cm). In contrast, in PTL from 0-10 cm, $Ca^{+2}$ significantly increased σ: 120 vs. 90 kPa in PTL-T0; 128 vs. 111 kPa in PTL-T1; and 183 vs. 152 kPa in PTL-T2. At depths of 10-20 and 20-30 cm, σ was neither affected by $Ca^{+2}$ nor by PTL treatments, with average values of 146 and 190 kPa, respectively. Calcium application in the first 10 cm increased the soil bearing capacity in the PTL facilitating machinery traffic, while in the PCB it promotes soil structure regeneration, which is favored by the absence of compaction associated with the CMT system. Further evaluations are required to verify the effect of calcium on structural stability in the PCB and the evolution of σ in the PTL with successive traffic.

**Key-words:** calcium sulfate, calcium hydroxide, permanent traffic lanes, permanent crop bed, pre-compression pressure

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# Effects of grass hedgerow measures on physical crust development and slope runoff and sediment of southern Quaternary red clay in China

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## ABSTRACT

Soil erosion represents a global environmental challenge that directly influences cropland quality and the sustainable use of soil resources, but indirectly affecting the turnover of soil C, climate change, and food security.The red soil region in southern China, under the combined influence of natural and anthropogenic factors, has become one of the most severely affected areas in terms of soil erosion. Physical soil crusts (PSC), defined as dense structural layer formed on the surface of bare or very low-cover land due to raindrop splashes or runoff, alter soil surface characteristics and significantly affect water infiltration and surface runoff generation. Although existing studies have demonstrated the widespread occurrence of PSCs in red soil regions due to local rainfall patterns and climatic conditions, the dynamic evolution of PSCs during rainfall events remains poorly understood. Furthermore, grass hedgerow serves as an effective biological measure for mitigating soil erosion by reducing surface flow velocity and erosive power through their aboveground biomass and root systems, while simultaneously enhancing soil physicochemical properties, fertility, and nutrient retention. However, the role of grass hedgerow measure in modulating the development of PSCs and their effectiveness in controlling erosion at different stages of crust formation remains unclear.

This study investigated the formation and erosion characteristics of PSCs developed on Quaternary red clay in typical red soil regions of southern China. Field-simulated rainfall experiments were conducted at an intensity of 30 mm/h. The research consisted of three components:
(1) Crust development process: PSC samples were collected at rainfall durations of 10, 30, 60, 90, and 120 min using PVC cutting rings. The pore structure and crust thickness were quantitatively characterized through X-ray computed tomography (CT) scanning, revealing the developmental process and structural characteristics of red clay crusts.
(2) Influence of grass hedgerows: Micro-plots were established within grass hedgerow systems. After 60 min of rainfall, soil samples were taken at varying distances from the hedgerows and analyzed via CT to assess spatial differences in pore parameters and crust thickness, thereby evaluating the mitigating effect of hedgerows on crust formation.
(3) Erosion response of crusted surfaces: Pre-formed crusts at different developmental stages (induced by 10–90 min of prior rainfall) were subjected to simulated rainfall to measure runoff and sediment yields. The total production of runoff and sediment was calculated for analyzing the effects of different stages.

Key findings from this study include: (1) The development of physical crusts in red clay exhibits distinct temporal stages: an initial stage characterized by particle detachment and pore filling, a middle compaction stage driven by raindrop impact, a late stabilization stage, and a final erosion stage. During crust formation, the thickness of PSC initially increases before stabilizing. The developmental trend fits a cubic equation: $y = 10.17 - 4.69x + 2.49x^2 - 0.30x^3$ ($R^2 = 0.8823$). At each developmental stage, the two-dimensional and three-dimensional pore structures of the crusts display unique morphological features. (2) Grass hedgerows significantly affected the spatial distribution and structural heterogeneity of soil crusts, with the crusts thinnest within the hedgerow and thickest between the hedgerows. (3) The development of PSCs accelerated the generation of runoff and suppressed sediment yield, with runoff increasing exponentially and sediment production stabilizing when a threshold of crust thickness was reached. Incorporating crust thickness into sediment-prediction models improved estimation accuracy by 18.6 % compared to conventional models based on rainfall indices, while maintaining comparable runoff-prediction performance.

These findings indicate the dual role of PSCs in promoting runoff but limiting soil loss, providing fundamental insights for optimizing hedgerow design, managing soil crust, and designing strategies to control erosion in sloping cropland in the southern red-soil region of China.

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# Interfacial hydrodynamic isotope fractionation of infiltrating rainfall in soil pore water is independent of evaporation

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**ABSTRACT**

Quantifying how rainwater infiltration modifies stable isotope composition in soil pore water is crucial for traci ng critical zone water movement. Tr aditi-onally, isotopic differences are a ttributed to evaporative fractionation or sampling artifacts. However, grow ing evidence suggests non-evaporativ e fractionation occurs during water movement, with underlying physics u nclear.

We monitored intact soil columns un der natural rainfall at high temporal resolution, jointly measuring seepage flux (Q) and drainage water isotopes (δ18O, δ2H). Data reveal a robust th reshold pattern: faster seepage consist ently correlates with more depleted i sotopes, unexplained by evaporation or mixing alone. Specifically, signific ant negative correlations exist at low flux ($Q < 0.2$ mm ·min-1·cm-2; δ2O: $r \approx -0.33$, $p < 0.001$), but disappear at high flux ($Q \geq 0.2$). Drainage data p lot above the Local Meteoric Water Line in dual-isotope space.

We propose the Interfacial Hydrodyn amic Fractionation (IHF) hypothesis. At low Q, prolonged pore-water int erface contact preferentially mobilize s lighter isotopologues, transiently re taining heavier ones, yielding deplete

d drainage. Above a critical Q, shortened residence times "short-circuit" matrix exchange, making efflue nt isotopes resemble input rainfall. IHF is a transport-controlled, non-equilibrium process independent of phase change.

This finding challenges frameworks attributing isotopic offsets solely to evaporation or mixing. IHF provides a hydrodynamic basis for ecohydrological separation, implying that estimating evaporative losses and recharge sources must account for flux-dependent fractionation. Future work should test IHF's generality across soils and climates and integrate it into models to improve water cycle predictions under climate change.

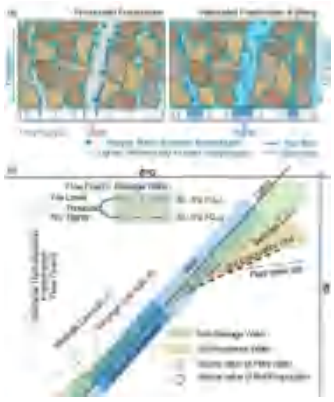


Figure. Flux-threshold interfacial hydrodynamic fractionation (IHF) in vadose-zone seepage: comparison with LMWL and SEL. a Pore-scale conceptual model. Left: Low flux enhances interfacial exchange, retarding heavier isotopologues at interfaces while mobilizing lighter ones. Right: High flux shortens residence time, muting fractionation. b Seepage-line framework. If IHF is widespread, source-value estimates based on LMWL intersections require reassessment. We define Seepage Line-I (low flux) and Seepage Line-II (high flux) to reflect flux-dependent behavior, highlighting flow-path divergence and incomplete matrix exchange.

**References**

Peng Zhao, Ying Zhao, Chengcheng Xia, et al. Interfacial hydrodynamic isotope fractionation of infiltrating rainfall in soil pore water is independent of evaporation, Communications Earth & Environment, 2026.

# Pore Structure–Controlled Water and Solute Transport in Agricultural Soils of Plain River Network Areas

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**ABSTRACT**

The plain river network (PRN) areas are major high-yield agricultural regions in China, where intensive fertilizer and pesticide use has resulted in serious agricultural non-point source (NPS) pollution. Soil pore structure plays a critical role in regulating NPS generation and transport by controlling water flow pathways and solute migration. However, conventional static fractal parameters are insufficient to characterize actual transport pathways within complex pore networks. To address this limitation, we introduced the spectral fractal dimension (d), a dynamic indicator of pore connectivity derived from random walk theory.

Soils from agricultural fields in the Jiangsu PRN region were investigated, covering the spatial continuum from field interiors to field bunds. High-resolution X-ray CT images were used to quantify pore morphology and heterogeneity, including mass fractal dimension ($D_m$), surface fractal dimension ($D_s$), and the dynamic connectivity parameter (d), across different soil depths. Seepage processes were simulated using AVIZO to quantify multidirectional water flow velocities and to evaluate the influence of pore structure on flow redistribution under irrigation conditions. Solute transport parameters were obtained from breakthrough curves and interpreted using the continuous time random walk (CTRW) framework.

The results showed that surface soils exhibited higher pore abundance and greater structural complexity, resulting in higher solute transport velocity (v) and diffusion coefficient (E) than deeper layers. Pore morphology and heterogeneity ($D_m$ and $D_s$) primarily controlled v and E by facilitating preferential flow pathways and enhancing solid–liquid interactions. In contrast, pore connectivity (d) dominated anomalous transport behavior (β) and solute arrival times ($t_1$, $t_2$) by regulating tortuosity and solute retention. AVIZO-based simulations further demonstrated that pore structural differences significantly influenced vertical and lateral flow velocities. These findings highlight the importance of dynamic pore connectivity in assessing subsurface transport processes and NPS pollution risks in PRN areas.

**Acknowledgments**

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# Microscale biophysical interactions determine environmental microbial ecology

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**ABSTRACT**

Microscale biophysical interactions at numerous interfaces are critical for microbial life and ecological functioning. Combining novel microscale experimental observations with agent-based computational modeling, we illustrate how microbial intrinsic characteristics function to facilitate dispersal and subsequent interactions among microbial populations and with environments. Bacterial active motility emerged as a key trait facilitating dispersal and early-stage colonization. The surface-attached bacterial life-form likely intensified mineral dissolution and thereby enhanced element cycling. As a consequence, it promoted bacterial population proliferation which further reinforced localized interactions between bacteria and minerals. However, the advantages conferred by cell motility were significantly reduced under constrained pore water configuration (drier soil conditions). Under such conditions, non-motile bacteria relied on passive dispersal mechanisms or physical adhesion to colonize the porous surfaces. Furthermore, functional metagenomic profiling of the colonizing microbial populations uncovered a trade-off between growth and dispersal rates. This observed trade-off was incorporated into an agent-based model simulating microbial activity in soil, which explored how correlations between microbial functional genes influence community dynamics during early colonization. The simulations demonstrated that the growth dispersal trade-off is crucial for enhancing and maintaining microbial diversity during colonization of new niches. These microscale quantitative estimations on biophysical interactions provide new insights into mechanistic understanding of microbial functionalities in regulating the biogeochemical processes of soil elements.

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# Effects of Different Land Uses on Soil Structure and Hydrological Function: Mechanisms and Implications

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## ABSTRACT

To systematically elucidate the mechanisms by which typical land use practices affect soil hydrological functions on the Loess Plateau, this study investigated cropland, grassland, and shrubland through a combination of field in-situ observations and laboratory analyses. The assessment focused on soil physicochemical properties, aggregate stability, and hydraulic characteristics under the three land use types. The results indicated: (1) Surface soil under shrubland exhibited the most favorable physical structure, with significantly higher soil organic carbon content (28.18 g/kg) compared to cropland (7.79 g/kg) and grassland (10.81 g/kg), along with the highest aggregate stability (MWD, R0.25, D) and the lowest bulk density. (2) Shrubland demonstrated the strongest integrated hydrological function, characterized by significantly superior initial water content (18.39%), stable infiltration rate, and water-holding capacity under high suction compared to the other land use types, forming a "soil reservoir" that effectively combines high infiltration capacity with strong water retention and conservation. (3) Correlation analysis revealed that total soil porosity, root biomass, and aggregate stability are key factors regulating soil hydraulic functions. This study demonstrates that prioritizing shrub vegetation in ecological restoration efforts on the Loess Plateau can synergistically enhance soil water conservation and erosion resistance, providing a scientific basis for optimizing regional land use and ecological rehabilitation.

**Keywords:** Loess Plateau; Land Use; Soil Aggregate Stability; Soil Hydraulic Properties

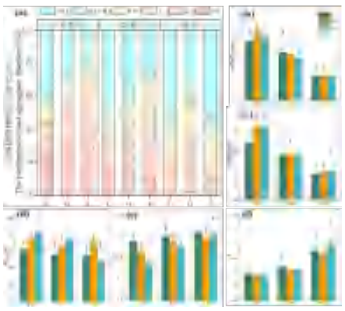


Fig. 1. Size distribution (a) and stability indicators (b–f) of soil aggregates across different soil layers under various land use types. C, cropland; G, grassland; S, shrubland. MWD, mean weight diameter; GMD, geometric mean diameter; R0.25, percentage of water-stable aggregates >0.25 mm; D, fractal dimension of aggregates; K, soil erodibility factor.

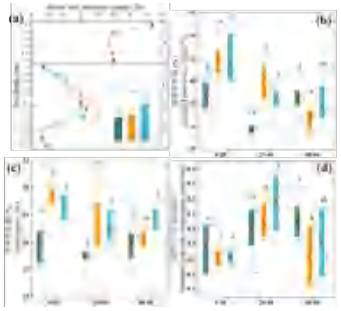


Fig. 2. Variations in soil initial water content (a), saturated water content (b), field capacity (c), and saturated hydraulic conductivity (d) with soil depth under different land use types. C, cropland; G, grassland; S, shrubland.

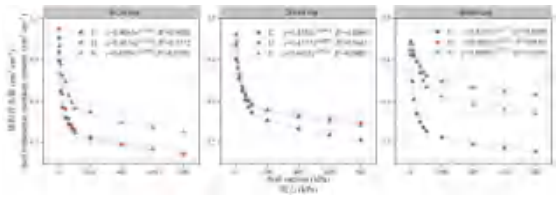


Fig 3. Soil water characteristic curves across different soil depths under various land use types. C, cropland; G, grassland; S, shrubland.

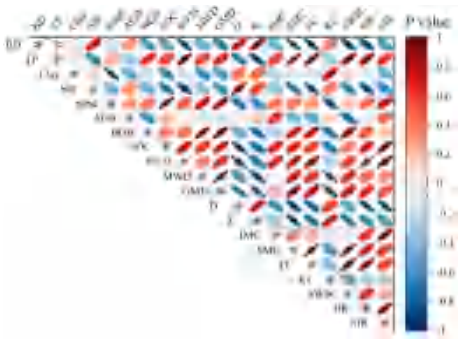


Fig. 4. Correlation heatmap between soil hydraulic property parameters, soil physical characteristics, and vegetation biomass.

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# Characteristics of Aggregates and Their Response to Nutrients in Dark Brown Soil under Different Nitrogen and Phosphorus Fertilizer Levels

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**ABSTRACT**

[Objective] This study aims to investigate the relationship between soil aggregate stability and soil nutrients under different nitrogen and phosphorus fertilizer levels, to provide a scientifically sound fertilization strategy for improving brown soil structure. [Methods] Based on the long-term fertilization experiment of dark brown soil initiated in 1979 by the Heihe Branch of Heilongjiang Academy of Agricultural Sciences, 12 treatments, including no fertilization ($N_0P_0$) as the control and applied agricultural manure (M), straw returning to field (S), and different NP levels: low, medium, and high quantitative fertilization ($N_1P_1$, $N_2P_2$, $N_4P_4$), wheat straw returning to field + different NP levels ($N_1P_1S$, $N_2P_2S$, $N_4P_4S$), agricultural manure + different NP levels ($N_1P_1M$, $N_2P_2M$, $N_4P_4M$) were used in this study. Soil samples from the 0–20 cm layer were collected for each treatment with three replication, and aggregates were sieved into four grades using the wet sieving method. The mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates were calculated, and soil pH, soil organic matter (SOM) and nutrient content were measured. [Results]Compared with $N_0P_0$, NP treatment significantly increased the proportion of>2 mm soil aggregates (12%-62%), with the change trend being $N_2P_2$> $N_4P_4$> $N_1P_1$. Under NPS treatment, the proportion decreased with increasing NP levels. In NPM treatments, the proportion followed the order of $N_1P_1M$> $N_4P_4M$> $N_2P_2M$. Compared with $N_0P_0$, NP treatment significantly increased the mean weight diameter (MWD) of soil aggregates (14%-45%), with MWD showing the order of $N_2P_2$> $N_4P_4$> $N_1P_1$with NP levels increasing. Under NPS treament, MWD decreased with increasing NP levels. In NPM treatments, MWD followed the order of $N_1P_1M$> $N_4P_4M$> $N_2P_2M$, with $N_2P_2$ exhibiting the largest MWD. Compared with NP treatments, both NPS and NPM treatment significantly increased soil pH and SOM content. Under NP, NPS, and NPM fertilization, pH decreased with increasing NP levels. The SOM content in NP treatments followed the order of $N_4P_4$> $N_1P_1$> $N_2P_2$, while the order in SOM content under NPS treatments was $N_2P_2$> $N_1P_1$> $N_4P_4$. In NPM treatments, the order of SOM content was $N_2P_2M$> $N_4P_4M$> $N_1P_1M$. Among the combincation of organic and inorganic fertilizers, $N_2P_2S$ and $N_2P_2M$ performed well. Correlation analysis revealed a significant negative correlation between soil organic matter content and both MWD and GMD ($p<0.05$), which were contrary to previous studies,this may be attributed to the higher SOM and C/N ratio background values. The random forest model indicated that the carbon-to-nitrogen ratio (C/N) was the most significant factor influencing soil aggregate stability (MWD). [Conclusion] The combination of organic and inorganic fertilizers significantly increased soil pH, significantly suppressed soil acidification, and enhanced aggregate stability. Among the treatments, $N_2P_2M$ and $N_2P_2S$ demonstrated superior effects compared to other fertilization methods.

**Keywords:** dark brown soil; long-term fertilization; different nitrogen and phosphorus level combinations; aggregate stability

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# Effects of Spatial Resolution on Spectral Characteristics of Soil Salinity in Plastic-Mulched Farmland

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**ABSTRACT**

Spectral remote sensing enables efficient acquisition of large-scale land surface information and is a key approach for monitoring soil salinity content (SSC). Plastic-mulched cultivation is the main planting practice adopted in salt-affected arid and semi-arid regions to cope with water–heat imbalance, resulting in most areas being covered by plastic mulch or vegetation for the majority of the time, with bare soil periods difficult to capture. At the same time, surface mulching significantly alters the spectral characteristics of croplands, increasing the uncertainty of SSC retrieval using remote sensing. Based on multi-resolution remote sensing data derived from plastic mulch geometric parameters, this study systematically analyzed the spectral features sensitive to SSC under different mulching conditions and evaluated the effects of spatial resolution on SSC spectral responses. Results indicate that under near-ground ultra-high-resolution conditions, the correlation between inter-mulch bare soil spectral features and SSC is weakly influenced by mulch type, and distinguishing mulch types provides limited improvement in inter-variable relationships. In contrast, under multi-resolution settings at the field scale, separating black-mulched, white-mulched, and non-mulched fields significantly enhances the correlation between spectral indices and SSC, with the coefficient of determination ($R^2$) based on the recursive feature elimination (RFE) algorithm increasing by up to 0.28. The highly sensitive spectral indices of non-mulched farmland are generally consistent with those of white-mulched farmland, but differ markedly from those of black-mulched farmland. Regarding scale optimization, the optimal spatial resolution is 1.35 m for white-mulched and non-mulched farmland, whereas black-mulched farmland performs best at 5.4 m. These findings provide methodological guidance and practical approaches to accurately retrieve SSC in plastic-mulched croplands and to determine the optimal image spatial resolution.

**Keywords:** Soil salt content; Plastic mulching; Spectral characteristics; Spatial resolution; Feature selection; Remote sensing

# Sensitivity analysis of agricultural hydrological processes to climate change in the North China Plain

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**ABSTRACT**

Climate change is exerting profound impacts on hydrological cycles, posing significant threats to agricultural sustainability and water resource security. Quantifying the sensitivity of agro-hydrological processes to climate change is therefore critical for developing effective adaptation strategies. This study employed a calibrated and improved Soil and Water Assessment Tool (SWAT) model and sensitivity analysis to assess the sensitivity and contributions of key climatic factors to major agro-hydrological variables in the North China Plain (NCP) from 1966 to 2016. The region exhibited a marked warming and drying trend, with minimum temperature rising more rapidly (0.56 °C 10 $a^{-1}$) than maximum temperature (0.12 °C 10 $a^{-1}$). While precipitation and solar radiation decreased 3.98 mm 10 $a^{-1}$ and 0.51 MJ·$m^{-2}$ 10 $a^{-1}$, respectively. Actual evapotranspiration ($ET_a$) was more sensitive to air temperature during the winter wheat season but to solar radiation during the summer maize season; Irrigation demand showed strong positive sensitivity to air temperature and solar radiation but negative sensitivity to precipitation; and water yield demonstrated exceptionally high sensitivity to precipitation, especially at the main watershed outlet. Contribution analysis further indicated solar radiation as the dominant factor governing actual evapotranspiration variation, whereas precipitation was the primary driver for changes in water yield. These findings provide a quantitative basis for crafting targeted water management policies, such as optimizing irrigation scheduling and reinforcing flood control infrastructure, to enhance climate resilience in this vital agricultural zone..

**Keywords:** Enhanced SWAT model; Agro-hydrological elements; Climate factors; Sensitivity analysis; Contribution estimation; North China Plain

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# Mechanical Adaptive Feedback Mechanisms of Microbial Colonies to External Physical Pressure

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**ABSTRACT**

External physical pressure, such as desiccation stress induced by drying-rewetting cycles, is common in natural environments, and is critical for bacterial sessile life forms including biofilms. This confining pressure may directly dictate the spatial configuration of mechanical interactions among cells, and subsequently impacts their growth and range expansion. However, how does such external pressure, conspiring with intrinsic cellular characteristics (e.g., mechanosensitivity, cell aspect ratio), function to shape bacterial cell-cell interactions and emergent community structures remains largely unknown.

Employing individual-based and continuum models, we quantitatively illustrate how single cell scale mechanical responses to the physical stress trigger bacterial collective performance including population growth, range expansion and potential transitions into growth-arrested states.

The study specifically investigates how stress-responsive bacteria adjust internal states such as cell-length diversity and spatial reorganization, thereby modifying internal stress generated by cell-cell contacts and tuning the colony's overall mechanical resistance to external isotropic pressure. The stage of colony development critically influences these adaptive outcomes, as the pre-existing internal stress and structural state of the biofilm vary significantly with its size and age. The mechanical framework established in this work provides a theoretical foundation for understanding how soil microbial communities modulate internal stress to enhance mechanical resilience under external physical constraints, offering important insights into the effects of soil physical processes such as drying-rewetting cycles on microbial ecological functioning.

# Impacts of precipitation and heat changes on agricultural water resources and grain production in the North China Plain

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**ABSTRACT**

Climate change poses severe challenges to water resources and food security. As a vital breadbasket of China, the North China Plain urgently requires quantitative research on the sustainability of its agricultural water resources and the response mechanisms of crop production to climate change. This study employed an improved SWAT(Soil and Water Assessment Tool) model, combined with long-term (1966–2016) meteorological data and multi-scenario simulations, to quantitatively analyze the impacts of changes in precipitation, temperature, and solar radiation on agricultural hydrological processes and crop yields. The results show that from 1966 to 2016, the maximum and minimum temperatures in the study area increased significantly at rates of 0.12°C and 0.56°C per decade, respectively, while precipitation and solar radiation exhibited declining trends. Spatially, the southern region exhibited higher actual evapotranspiration (annual mean 790.4 mm), irrigation water use (annual mean 359.6 mm), and rates of shallow groundwater decline (annual mean 1.9 $m \cdot a^{-1}$) compared to the northern region. Climate change scenario analysis indicated that increased precipitation boosted winter wheat yields, whereas summer maize yields slightly decreased (≤1%) under precipitation increases of 5%–20%. A 20% reduction in precipitation led to increases in irrigation demand and groundwater decline rates by 10.5% and 21.0%, respectively. Rising temperatures primarily exerted negative impacts on crop yields, while changes in solar radiation had a more pronounced effect on maize production. This study provides a scientific basis for optimizing agricultural water resource allocation and formulating climate-adaptive cropping strategies in the North China Plain, with significant implications for ensuring regional food security and sustainable water resource utilization.

**Keywords:** North China Plain; Climate Factor Change; Crop Yield; Agricultural Hydrological Elements

# Sea weed contribute enormous number of charges to soil system and enhances massive rice productivity

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**ABSTRACT**

To investigate the distribution of the electric charges, by the effects sea weed and some non-traditional compost was made by potentiometric titration method of net electric charge measurement for assessing the effects of these composts on rice productivity. For this purpose, soil incubated with sea weed and some nontraditional composts and analyze it on various electro-chemical charge character along with pot and field study on rice production. The surface charge of variable charge constituents depends on the pH and ionic strength of soil solution. Organic carbon strongly affects the variation of negative charge with pH, but sesquioxide or allophone is responsible for positive charge variation. Variable surface charge is attributed to the ionization of functional groups on organic matter, hydrous Fe and Al oxides, and edge sites on clay by protonation and de protonation processes. Soil charge formation is regulated by the nature of organic matter, clay and sesquioxide Sea weed influence more on ZPC shifted it to lower range indicate that it contributes enormous amount of soil charge to soil system that's accelerates ionic movements and rice productivity.

**Keywords:** Electro-chemical charge, Sea weed, non-traditional compost, nature of organic matter& clay, sesqoxide, allophane, and rice productivity.

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# Floodplain Wetlands as Biogeochemical Filters Following Wildfire

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## ABSTRACT

Wildfires in high elevation headwater forests are occurring more frequently and at greater severity due to climate change. Within watersheds following wildfire, perennially saturated wetlands may slow surface runoff and help filter sediment, ash, char, and dissolved chemical solutes, all of which cause issues for water quality and downstream water users. To increase retention of surface water, groundwater and sediment, wooden structures that mimic beaver dams have been installed within stream channels and the surrounding floodplain in a watershed within the Rocky Mountains, Colorado that burned during the 2020 Cameron Peak Fire. One objective of this project is to evaluate the potential of montane floodplain wetlands as natural biogeochemical filters following wildfire and further assess how increased saturation from dam installation may alter these processes. To address this objective, we conducted a greenhouse experiment with custom-made rhizoboxes using plants and soil collected from the field site. We introduced a burned (450ºC) soil extract once plants maturated (~3 months) to investigate how biogeochemistry responds to a pulse of pyrogenic material. Furthermore, to understand how in stream structures and the resulting increased floodplain inundation impacts biogeochemistry, we conducted this experiment with three water level treatments: fully flooded, semi-flooded and drained. We quantified in-situ porewater chemistry (i.e., pH, redox, DOC, UV-VIS-EEMs), plant-soil gas flux (i.e., $CO_2$, $CH_4$, $N_2O$, $NH_3$), soil microbial analysis, root growth, along with planar optode $O_2$ soil profile imaging. Our results show that after the addition of pyrogenic material, a significant pulse of $CO_2$ from the soil occurred and lasted for ~1 month. This pulse turned the systems from net sinks of $CO_2$ to net sources. Interestingly, there was no subsequent increase in total porewater dissolved organic carbon (DOC) following addition of the pyrogenic material, but changes to porewater DOC characteristics (i.e., UV-VIS-EEMs parameters) were detected. This indicates that DOC characterization, rather than concentration, drove the increase in soil $CO_2$ flux. Furthermore, we found evidence for plant-mediated transport of $CH_4$ in our systems, as $CH_4$ flux measurements obtained under full light saturation were significantly greater than $CH_4$ flux measurements observed with no light. This points to a mechanism where $CH_4$ may be escaping through leaf stomata when the stomata are open during photosynthesis (i.e., when lights are on) compared to when they are closed (i.e., when lights are off). Our findings exemplify the ability of montane wetlands to act as a natural biogeochemical filter following wildfire and provide insight into the management of floodplains following wildfire. Furthermore, we find that our integrated experimental approach is applicable and adaptable to a wide range of plant-soil settings and scenarios, particularly at the soil-plant-atmosphere interface.

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# Potassium mineralization potentials of some soil amendments applied to a degraded tropical Ultisol

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**ABSTRACT**

Understanding Potassium (K) mineralization pattern of soil amendments is critical in proper K fertilizer management. This study evaluated the potassium (K) mineralization potential of selected soil amendments applied to a degraded Ultisol during a 90 day incubation period. The objective was to assess the effects of these organic amendments and period of incubation on the release and availability of exchangeable K and to examine the relationships between K dynamics and selected soil properties during a 90-day incubation period. The experiment was arranged in a 4 × 10 factorial experimental set-up fitted in a Completely Randomized Design. Treatments were soil amendments (Control, poultry manure, biosolids, and biochar) and period of incubation (0, 10, 20, 30, 40, 50, 60, 70, 80, 90 days). Physico-chemical properties of both the soil and the amendments were characterized prior to incubation. Exchangeable K was measured at 10 day interval to monitor the rate and pattern of K mineralization. The results showed marked effect of both the soil amendments and period of incubation on K mineralization. The results revealed that all the amendments significantly increased exchangeable K concentrations relative to the unamended control, indicating enhanced nutrient release and improved soil fertility status. Among the treatments, poultry manure exhibited the highest and most rapid K release, reaching a peak concentration at 60 days of incubation, reflecting its high nutrient content and fast mineralization rate. Biochar demonstrated a steady and sustained K release throughout the 90 days, suggesting its long-term potential to maintain nutrient availability and reduce K losses through leaching. In contrast, biosolids produced the lowest increase in exchangeable K, indicating limited contribution to K mineralization. Correlation analysis showed strong positive relationships between exchangeable K, soil pH and exchangeable calcium, implying that amendments that increased soil pH and base cation content enhanced K availability and retention in acidic soils. Negative correlations with sodium and phosphorus suggested possible nutrient interactions or competition among cations. The study demonstrated that poultry manure and biochar are highly effective organic amendments for improving K mineralization, soil fertility, and nutrient balance in acidic Ultisol.

# The effect of endogenous hydrogen on the soils of the degassing sites of the Central Chernozem region of the Russian Federation

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**ABSTRACT**

The manifestations of degassing are found on almost all continents and are well deciphered in the satellite images. They are either lightened spots and circles that are clearly visible on the arable land of automorphic soils, or depressions experiencing temporary excessive waterlogging. The diagnostic indicator for their detection is the correct round shape and lightening of the upper humus horizon.

The soils affected by endogenous hydrogen are very different from the soils of the surrounding area, which are similar in hydrothermal conditions. According to our research, an intensive reductive regime is formed in chernozems exposed to hydrogen flux. The acidity increases dramatically, and carbonate neoplasms disappear. With an increase in the total humus content, the upper humus horizon lightens as a result of changes in the composition and properties of humus. The composition of humus in such conditions changes towards a fulvate type, unusual for chernozems, which indicates its high mobility. The presence of a large amount of aggressive fulvic acids in the soil mass is probably one of the reasons for the very strong acidification of the soil profile.

It should be noted that such soils have been studied before, but features mentioned above were attributed to the effect of temporary waterlogging, since the processes of hydrogen degassing were beyond the attention of scientists. A series of model experiments have been conducted to distinguish the effects of the waterlogging factor and the hydrogen flux factor on chernozem soils. The experimental results show that the effect of hydrogen flux and waterlogging on soils will be unidirectional, but different in intensity. Waterlogging slightly reduces the redox potential of the soil (by 100 mV), while (according to NMR13C data) there is a slight change in the fragment composition of humic acids, while incoming hydrogen reduces the redox potential to extremely low values (by 800 mV) and ensures the destruction of the peripheral part of humic molecules without destruction of aromatic clusters. In the presence of a hydrogen stream, the content of non-silicate iron compounds in the soil increases, and their ratio indicates an intensification of the gley process. The removal of organic matter into the soil solution increases, and an increase in the concentration of aluminum in the solution indicates the likely destruction of the crystalline lattices of aluminosilicates, which are part of the solid phase of the soil. These features are clearly reflected in the morphology of the soil profile and indicate the predominant processes of substance removal in soils exposed to intensive flux of endogenous hydrogen.

# Effects of repeated wetting and drying cycles on potassium fertiliser behaviour and nutrient dynamics in diverse soils

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## ABSTRACT

Improving soil potassium (K) availability is essential for plant nutrition, but K fertilizer efficiency is estimated to be only 19% globally for cereal crops. Repeated wetting and drying cycles are a defining feature of soils of all agricultural systems and have a marked influence on nutrient cycling and fertiliser behaviour by modifying soil structure, ion diffusion and binding, and redox processes. However, much remains unclear regarding the effects of wetting and drying cycles on K fertiliser behaviour, such as whether the form of K fertiliser applied alters K behaviour. One fertiliser of particular interest is polyhalite, as it co-supplies other cations (Ca and Mg) with K which may potentially reduce K fixation in soils with high fixation capacity.

In this study, we used eight highly diverse soils from Australia, the United States, the United Kingdom, Nigeria and China, dominated by different minerals, such as montmorillonite, illite-smectite, kaolinite and quartz. Soils were treated with polyhalite ($K_2SO_4MgSO_42CaSO_4 \cdot 2H_2O$) or sulfate of potash (SOP) at a rate of 1.20 g K $kg^{-1}$ soil, equivalent to 150 kg K $ha^{-1}$. We simulated the fertosphere conditions (the fertiliser-enriched soil around the granule) to better understand the reactions that drive the availability of K. Soils were then incubated and subjected to various wetting and drying cycles (0, 2 and 8 cycles), alternating between 20 and 80% of water holding capacity (WHC). Each cycle consisted of approximately 24 h of wet incubation followed by 16–20 h of drying at 25 °C.

It was found that repeated wetting and drying cycles substantially altered K partitioning and speciation across these diverse soils. In soils containing minerals with a high capacity to fix K (such as illite and muscovite), wetting drying cycles promoted the fixation of K within interlayer sites. In contrast, soils dominated by highly weathered minerals, such as those from Australia, had minimal K fixation. Other than K fixation, the form of K was most closely related to clay content and cation exchange capacity (CEC) – soils with a high CEC had increased exchangeable K whilst soils with a low CEC had higher concentrations of soluble K. We also examined the effect of the K form supplied (SOP or polyhalite) on K behaviour, with the co-supply of Ca and Mg from polyhalite slightly reducing K fixation by competing for exchange sites and modifying cation equilibria. Finally, preliminary K-edge X-ray absorption near edge structure (XANES) analyses revealed corresponding spectral shifts, confirming the progressive transformation of K speciation under repeated wetting and drying cycles.

Overall, repeated wetting and drying cycles altered K availability in a soil-specific manner. High-clay soils with K-fixing minerals had reduced K availability whilst sandy and highly weathered soils had higher K availability. It was also found that co-supply of Ca and Mg from polyhalite can potentially decrease K fixation.

# Impact of Saltwater Intrusion on Phosphorus Speciation and Mobility in an Agricultural Soil

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**ABSTRACT**

Saltwater intrusion, resulting from sea level rise, poses threats to agricultural areas along the coastlines by altering soil physicochemical properties and porewater chemical compositions. These changes may affect phosphorus (P) speciation and lability, leading to P release into water bodies and associated environmental impacts. In this study, we utilized synchrotron-based X-ray absorption near edge structure (XANES) spectroscopy in combination with Mehlich-3 (M3) and Hedley sequential extractions to monitor changes in P speciation and mobility in an agricultural soil. A representative agricultural soil was selected from the lower Chao Praya floodplain of Thailand, amended with P in a form of potassium dihydrogen phosphate ($KH_2PO_4$), and saturated for up to 60 days with synthetic water of four salinity levels: 0.05, 0.2, 2, and 5 parts per thousand (ppt). Porewater was collected daily using rhizon samplers to monitor inorganic P ($P_i$) release. The results revealed that soil pH initially decreased and slowly rebounded beyond the initial soil pH for all salinity treatments. Exposure to high water salinity (i.e., 2 and 5 ppt) markedly increased soil electrical conductivity (EC), suggesting salt accumulation, while low water salinity (i.e., 0.2 and 0.05 ppt) slightly reduced soil EC. Chemical extractions showed a decrease in M3-extracted and water-soluble P over time; however, the proportions of these fractions were slightly higher in soil samples treated with high-salinity water compared to the low-salinity treatments, indicating higher soil P availability. This result corresponds with the higher $P_i$ concentrations in the porewater of the high-salinity treatments toward the end of saturation period. Furthermore, our XANES analysis identified iron (Fe), aluminum (Al), and smectitic clay minerals as the primary hosts for P in the studied soil samples. Overall, P became less labile over time due to an increase in the Fe-P phase and a decrease in clay-P proportion; however, soil treated with higher water salinities had less clay-P, possibly due to low pH and elevated salt ion concentrations that hinder P re-adsorption from porewater onto clay minerals. In summary, our work demonstrates that increasing salinity associated with sea level rise can enhance soil P availability and release, potentially accelerating nutrient losses from saltwater-intruded agricultural soils, while also rendering soils unfavorable for cultivation as salts accumulate. Further studies should determine how these salinity-driven processes unfold under field conditions and long-term sea level rise, with implications for sustainable nutrient management in saltwater-intruded agricultural landscapes.

# Soil development on coal-waste dump in southern Poland

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**ABSTRACT**

The spontaneous succession of vegetation on waste heaps resulting from coal exploitation has long aroused the interest of researchers around the world because these are places where plant succession processes and soil development can be observed and monitored from the moment of initiation.

The objectives of this study were: (i) to determine the joint development of vegetation succession, (ii) to establish its influence on soil formation processes and soil characteristics against the background of environmental conditions, and (iii) to determine the chemical composition of plants as an element enriching soils with nutrients in the early stages of succession on a post-mining coal-waste heap.

The study was conducted at the mining waste dump of the Szczygłowice Coal Mine in southern Poland.

The floristic examinations consisted of an inventory of plant species growing on the analyzed area in divided surfaces. The course of vegetation succession in the area of the coal-waste heap was examined along a transect which ran from the newest areas of heaps with freshly dumped post-mining waste, through sodded areas, to the emerging initial forest with a dominant share of R. pseudacacia. Vegetation changes were analyzed both on the basis of satellite imagery and by a direct field survey, including an analysis of drone images.

Three soil profiles were produced under dominant plant communities representing particular stages of succession: initial - profile 1, optimal - profile 2, and terminal - profile 3. In the initial stage of succession under algocenoses 5 soil samples were also taken. Dried soil samples were and analyzed, following the standard procedures namely, pH measured potentiometrically in H2O and in 1N KCl using a glass electrode, total organic C (%) according to Tiurin's method, total nitrogen (Nt) content using the Kjeldahl method, and hydrolithic acidity (Hh) according to the Kappen method. Total phosphorus (Pt) was measured using the Bleck method, available phosphorus (Pavail) by Egner–Riehm's method and available Kavail and Mgavail.

The Spearman's rank correlation coefficient was applied to check whether there was any relationship between the concentrations of the selected elements in both plant materials, soil materials and crust with algae at the study profiles.

It was found that changes in the development of vegetation is closely related to the stages of coal waste disposal, where the initial, transitional, and terminal stages were distinguished. The organic carbon content in all samples is high. The highest content of total nitrogen was found in the algal crust and Olf and A levels in the initial forest. Notable contents of available elements were found in the algal shell. The algal crust serves as a good environment for soil formation, as the first stage. Plant succession is initiated by species with a wide ecological tolerance in the area studied.

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# Salix acutifolia Willd. as an ecological engineer in the processes of soil formation and plant succession in sandy areas

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**ABSTRACT**

The processes of initiation of vegetation succession and soil development in the Błędowska Desert and other sandy ecosystems of the Silesian Upland are initiated mainly by the european violet willow *Salix acutifolia*, also known as the caspian willow. It is a pioneer species and is characterized by low habitat requirements. This species is the first to enter loose and bare sands after algae associations. In subsequent periods, as it develops, it increases its canopy and stabilizes the sand. This results in the systematic encroachment of herbaceous psammophilous species, especially *Pinus sylvestris*. The results show that nutrient accumulation is strongly associated with the canopy effect while nutrient accumulation is low or almost absent in the canopy gap spaces. Enriched zones under the canopy of *S. acutifolia*, reflecting the interaction of biotic and abiotic factors, are called fertility islands. The developing direct soil horizons in the canopy zone of willow vary in thickness depending on the distance from the trunk. The organic horizon and its sub-horizons create favourable conditions for the development and existence of soil organisms, which also affect the soil-forming process. Given the young age of the soil and the poor differentiation of soil horizons, the organic matter located directly above the mineral layer plays an important ecosystem role in the initial stages of vegetation succession and soil development. The quantity and quality of organic matter influences sorption capacity, degree of saturation with base cations and soil fertility. Broad-leaved species such as: *Salix acutifolia, Quercus robur or Betula pendula* positively influence the succession rate, causing the species diversifying through canopy effect.

The organic carbon content in all tested samples of *Salix acutifolia* ranges from 48.1 to 52.7%, with the highest concentration of this element found in fallen leaves. The concentration of total nitrogen in bark, fallen leaves and green leaves is 1.35%, 1.71% and 1.49%, respectively, and the C/N ratio in the tissues of these litter fractions ranges between 30 and 36. The nitrogen and phosphorus content is higher in fallen leaves than in green leaves.

Alkaline elements dominate in all organs, especially in the leaves. Hence, the pH of *S. acutifolia* leaves is less acidic than that of B. pendula. In the organic layer of the soil profile under *S. acutifolia*, aliphatic compounds dominate. Aromatic compounds also account for a significant proportion (9%). The predominance of aliphatic compounds in the humus layer is due to the poor mixing of organic matter with the mineral fraction, and organic compounds at this stage of soil succession in the humus layer originate primarily from the decomposition of dead roots of herbaceous plants and sharp-leaved willow shrubs. As communities become more complex and a distinct vertical structure develops, the proportion of lignin and polysaccharide derivatives increases.

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# Using radiogenic and metal stable isotope ratios as new tools to assess nutrient cycling in agricultural systems

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## ABSTRACT

Ratios of radiogenic and metal(loid) stable isotopes are well-established tools in geosciences to trace geological transformation processes. Although these processes also occur in agricultural systems, the application of these isotope ratios in agriculture is still poorly constrained. Apart from the fact that the isotope composition of metal elements like iron (Fe) and magnesium (Mg) differ between soil compartments and plants, agricultural practices often alter biogeochemical processes and thus isotope ratios in agri-systems. Therefore, analyzing these stable isotopes can help understand the cycling and use efficiency of key nutrients under agricultural conditions. In this presentation, we will present several examples of such applications in the investigation of long-term agricultural land-use and sustainable subsoil management funded by the Deutsche Forschungsgemeinschaft (DFG, PaddyFe Project, No. 391749090) and the Bundesministerium für Forschung, Technologie und Raumfahrt (BMFTR, BonaRes-Projects Soil$^3$, No. 031B0026C, 031B0515C, and 031B1066C).

Using Fe stable isotopes we reconstructed Fe dynamics in a paddy chronosequence, revealing that long-term rice cropping and subsequent redox cycle altered the biological contribution in the terrestrial Fe cycle. Long-term liming reduced Fe availability to crops due to the increased soil pH and promoted the Fe uptake strategy of the crop through complexation of Fe(III) from the rhizosphere. Long-term liming also altered the exchangeable Mg pool of the soil and its Mg isotope composition by promoting Mg uptake.

Using metal stable isotopes in the assessment of sustainable subsoil management allowed us to explore the potential of subsoil amelioration through deep loosening and compost injection in optimizing nutrient and water use efficiency for crops. We first conceptually showed that Mg use efficiency of crops can be solely quantified from Mg stable isotope ratios when lime is not applied. We further used the radiogenic strontium isotope ratio ($^{87}Sr/^{86}Sr$) to reveal changes of the nutrient uptake depth caused by subsoil management. A shift in the $^{87}Sr/^{86}Sr$ ratio of crops indicated that deep loosening with compost incorporation in a silty Luvisol deepened the depth of nutrient uptake, whereas no such shift was observed in crops grown in a sandy Retisol. This suggests that when water is not a limiting factor subsoiling with compost incorporation is an effective management strategy to improve nutrient utilization from the subsoil, whereas under water-deficit conditions subsoil amelioration primarily improves water uptake from the subsoil but not nutrient acquisition.

We conclude that non-traditional metal stable isotopes are a powerful tool in agricultural sciences as they allow insights into biogeochemical cycling of nutrient elements.

# Mapping Microscale pH Dynamics at Soil–Amendment Interfaces Under Fluctuating Moisture Conditions

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**ABSTRACT**

The incorporation of soil organic amendments creates decomposition hotspots, and the microscale variability of pH in soil-amendment hotspots is a critical driver of microbial activity and nutrient cycling. However, little is known about the pH dynamics at the soil–amendment interface, particularly under conditions of fluctuating moisture. In this study, we applied high-resolution planar optode imaging to monitor in situ microscale pH dynamics at the straw–soil interface in a typical fluvo-aquic soil during three consecutive drying–rewetting cycles. Two straw incorporation patterns—heterogeneous (patch) and homogeneous (uniform)—were compared to assess their effects on localized pH variations. The heterogeneous straw treatment induced pronounced acidification hotspots (pH < 6.6) concentrated around straw patches. During wetting, the acidic zones expanded radially outwards, accompanied by a progressive steepening of the pH gradient (up to 0.10 units $mm^{-1}$). Upon drying, water limitation caused these zones to contract inwards as the pH gradient flattened. In contrast, the homogeneous treatment exhibited dispersed, less intense acidification (pH 6.7–6.9) with smaller spatial and temporal fluctuations. Repeated drying–rewetting cycles promoted cyclic accumulation and depletion of formic and acetic acids at the straw–soil interface. The magnitude of both acidification and cation release ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$) diminished across successive cycles, indicating the progressive depletion of labile straw components. These findings highlight the importance of straw spatial arrangement in shaping microscale soil acidification under moisture fluctuations, offering valuable insights for optimizing crop residue management and predicting soil biogeochemical responses.

**Acknowledgments**

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# Dissipation of $^{13}$C-Sulfamethoxazole in Tropical Soils under Contrasting Management Systems and Microplastic Contamination

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**ABSTRACT**

Sulfamethoxazole (SMX) is an emerging contaminant commonly introduced into agricultural soils via manure and other organic amendments, where it can modulate microbial processes and contribute to the selection and dissemination of antimicrobial resistance genes. Its environmental persistence, transformation pathways, and ecological impacts, however, are strongly conditioned by land-use history, soil management practices, and the presence of co-occurring pollutants. This study investigated the dissipation of uniformly $^{13}$C-labeled SMX in parallel soils under three contrasting management systems: native forest, a soybean-maize rotation with limited cover-crop diversification, and a soybean system with a more diversified cover-crop mixture. For each soil, dissipation was assessed with and without polyethylene microplastics. Soils were amended with cattle manure spiked with $^{13}$C-SMX to achieve a final concentration of 442 µg kg$^{-1}$ and incubated for 42 days under controlled conditions (semi-dark room at 25 ± 2 °C). Polyethylene microplastics were incorporated at 0.14% (w/w), reflecting environmentally realistic levels in agricultural soils. Extractable $^{13}$C-SMX was quantified by LC-MS/MS using an optimized extraction protocol with high recovery and analytical sensitivity. SMX dissipation was very fast across all soils, with more than 70% loss within 7 days. Estimated half-lives ranged from 1.5 to 4.3 days, and microplastics only slightly increased dissipation rates. This rapid decline, faster than values commonly reported for temperate soils, likely reflects a combination of biotic and abiotic pathways: manure addition stimulated microbial co-metabolism, while Fe- and Al-rich mineral phases promoted sequestration of SMX-derived compounds into non-extractable residues. These results demonstrate that tropical soils can quickly attenuate sulfonamides, emphasizing that dissipation alone does not capture true degradability and must be interpreted separately from transformation and mineralization processes when evaluating antibiotic fate.

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# Understanding nutrient diffusion and availability from polyhalite fertiliser in contrasting soils

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## ABSTRACT

Potassium (K) fertilisers, particularly muriate of potash (MOP) and sulphate of potash (SOP), are widely used to increase crop yield. However, interest in alternative K sources is rising due to the vulnerability of traditional K fertilisers to global trade disruptions. In this regard, polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$) is a multi-nutrient mineral that also co-supplies calcium (Ca), magnesium (Mg), and sulphur (S), but the specific soil mechanisms and K release kinetics are poorly understood. To address this, we examined the nutrient release behaviour of polyhalite (POLY4® a granulated polyhalite product of Anglo American plc. (www.poly4.com)) in Australian highly weathered and calcareous loam soils, comparing its performance with SOP and MOP. Soils were incubated in Petri dishes with a fertiliser granule placed in the centre of the soil volume. Diffusive gradients in thin films (DGT) devices were then deployed to visualise and quantify, over time, the diffusion of potentially bioavailable K from the granules. The DGTs were analysed using X-ray fluorescence microscopy (XFM). After 56 days (d), incubated soils were sampled in four concentric rings of increasing distance away from the fertiliser granule and analysed for i) pH and electrical conductivity ii) nutrient fractions using sequential extraction and iii) potassium speciation using X-ray absorption spectroscopy (XAS). The K diffusion from MOP and SOP was faster than POLY4® after 3 d of incubation. However, after 7 d, SOP and POLY4® showed similar K diffusion, and between 14 to 56 d, all K sources exhibited comparable K diffusion distances. After incubation, some of the added Ca and S from POLY4® remained in the granule. In both soils at the fertiliser zone (0-1cm), while K forms from POLY4® were largely water-extractable, the majority of K forms from SOP and MOP were in the ammonium acetate extractable fraction. Additionally, Ca, Mg, and S forms in POLY4® were water-extractable forms at the fertiliser zone. These findings suggest that POLY4® acts as slow-release fertiliser, where its K release remains water soluble and less soil sorbed than when SOP or MOP are used.

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# What controls the metallomes of carrot and wheat grown under varying soil water conditions in greenhouse?

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**ABSTRACT**

Contamination of food crops by metals and metalloids (hereafter metals) poses increasing food safety risks. Both essential and toxic metals accumulate in crops and influence nutrition and human health, which necessitates the research on the plant metallome (the full composition of metals in plants). Nonetheless, how metallome profiles of different plant tissues change under variable soil wetting-drying periods and across growth stages remains poorly understood. This study investigated metal uptake, accumulation, and translocation in carrot (*Daucus carota* subsp. *sativus*) and wheat (*Triticum aestivum* L.) across growth stages under different soil wetting–drying regimes in a greenhouse experiment.

Both carrot and wheat were grown in a sandy soil with alternating dry (D) and wet (W) periods capped at soil water holding capacity of 35% or 80%. For carrot, the five growth stages were grouped into three phases, resulting in treatments (i.e., DDW, WDD, and WWW). Wheat growth was divided at Feekes 9 into two phases, resulting in three treatments (i.e., DW, WD, and WW). At the end of each growth stage of carrot and five selected Feekes stages of wheat, plant and soil samples were collected for each treatment in triplicates. The elemental analyses were performed by inductively coupled plasma – mass spectrometry (ICP–MS) after digestion following EPA 3051A method.

Multiple statistical analyses showed that plant growth stage was the primary determinant of metallome profiles in both carrot and wheat, with minimal influence from soil water conditions (except in wheat kernels). Hierarchical clustering of metal accumulation in aboveground tissues indicated that the clustering patterns were mainly driven by growth stage, while roots were less affected. ANOSIM and PCA confirmed that growth stage predominantly shaped metallomes in plant tissues, with limited impact from soil water conditions. However, wheat kernels showed different metal compositions among soil water treatments. Community analyses further revealed temporal changes in diversity and evenness, and distinct metal co-occurrence networks in different tissues based on Spearman correlation coefficients among metals. Translocation factors from roots to aboveground parts and bioconcentration factors highlighted dynamic changes in metal mobility across plant developmental stages and soil water conditions. Our ongoing work is exploring molecular mechanisms underlying crop metallomes using transcriptomic and metabolomic approaches.

**Acknowledgments**

This research was supported by Agriculture and Food Research Initiative Competitive Grant No. 2023-67017-40049 and the Hatch Act Formula Grant (MICL02823) from the USDA National Institute of Food and Agriculture. We also thank the Quantitative Bio-Element Analysis and Mapping (QBEAM) Center at Michigan State University for providing access to ICP-MS.

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# Process-Based Multi-Surface Modeling of Soil Arsenic: Enabling Large-Scale prediction of environmental fate and Guiding Remediation Strategies

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**ABSTRACT**

Accurate speciation analysis of inorganic arsenic (As) in soils is essential for predicting its environmental fate and transport. However, commonly used sequential extraction and advanced spectroscopic techniques suffer from substantial limitations: the former is labor-intensive, and the latter requires sophisticated instruments, making both unsuitable for high-throughput analyses. Our study aims to develop a process-based, multi-surface speciation model of As to enable high-throughput, broad-coverage prediction of As speciation in complex soil environments. In previous work, we identified and constructed surface speciation models of As on the surfaces of iron oxides [1] and clay minerals [2] based on microscopic interfacial mechanisms, while also quantifying the effects of coexisting cations and anions on As adsorption. Here, we further integrate multiple processes, interfaces, and ions to build a comprehensive multi-surface As speciation model (*Figure 1*). We particularly focus on identifying model-sensitive parameters and quantifying predictive uncertainties, aiming to pinpoint the key soil physicochemical properties that control As environmental behavior, minimize model parameterization, and maintain an acceptable error range. By combining this model with global soil databases, we are able to generate high-resolution, speciation-informed maps of As at the global scale. Overall, our study provides a robust and accurate tool for forecasting As behavior and fate in soils, highlights a bottom-up research paradigm linking microscopic speciation to macroscopic behavior, and ultimately offers valuable guidance for soil As remediation.

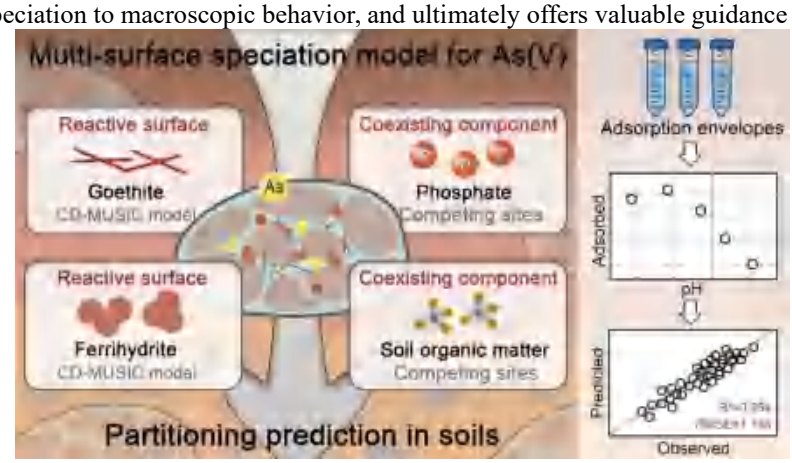



Figure 1 Multi-surface model construction based on multiple processes, interfaces, and ions

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# Chemical transformation pathways demonstrating elemental sulfur effectiveness in alkaline-sodic soils

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**ABSTRACT**

Elemental sulfur ($S^0$) is commonly used to improve alkaline–sodic soils, although its effectiveness can vary depending on soil physicochemical characteristics. We conducted a 60-week incubation study at 25 °C and 50% plant-available water content (PAWC) using six highly alkaline–sodic soils from Queensland (pH 9.0–10.0) to evaluate the remediation potential of $S^0$. Three sulfur sources—micronised sublimed sulfur, DEVCO sulfur-bentonite, and SWANCORP sulfur-bentonite—were applied at six rates (0, 0.25, 0.5, 1.0, 1.5, and 2.0 t $ha^{-1}$). Proton concentration, electrical conductivity (EC), and sulfate-sulfur ($SO_4$-S) concentration were measured at 0, 6, 12, 24, 40, and 60 weeks to track sulfur oxidation and associated changes in soil chemistry. Elemental sulfur application increased proton concentration by 20–50-fold, raised EC from approximately 0.3–0.9 to 4–5 dS $m^{-1}$, and increased $SO_4$-S concentration from 7–60 to 90–130 mg $kg^{-1}$ (a 2–20-fold increase), demonstrating substantial sulfur oxidation and the accumulation of sulfate and soluble reaction products. These coordinated increases indicate that $S^0$ effectively drives chemical transformations required for ameliorating alkaline–sodic soils. Overall, application rates of 1.0–2.0 t $ha^{-1}$ produced the strongest improvements while remaining within acceptable salinity thresholds. Our results provide soil-specific guidance for optimising elemental sulfur use in the reclamation of alkaline–sodic soils, aligning with previous findings that elemental sulfur improves soil chemical properties, as demonstrated by Akay et al. (2019).

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# Persistence, Transport and Transformation of Per- and Polyfluoroalkyl Substances in Soils from repeated Land Application of Biosolids

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**ABSTRACT**

A large portion of biosolids generated from wastewater treatment plants are applied to agricultural land for their plant nutrient values and as soil amendment to improve soil health. Many biosolids contain elevated levels of emerging pollutants, especially per- and polyfluoroalkyl substances (PFAS). The repeated land applications of biosolids could lead to increasing PFAS accumulation in soil and leaching down to groundwater. In this study, we collected soil samples at soil profile depths down to 180 cm and corn/wheat grains produced at the site which have received the repeated land application of biosolids for > 20 years. In this study, we applied the EPA 1633 analytical method targeting 43 PFAS in soils and grains collected in 1999, 2006, 2012 and 2018. Twenty out of 43 targeted compounds were identified and quantified at the levels of micrograms per kilogram of soil, which included legacy PFAS (e.g., perfluoroalkyl carboxylic acids and perfluoroalkyl sulfonic acids) and PFAS precursors (e.g., polyfluoroalkyl phosphate dieasters and perfluorooctane sulfonamidoacetic acids). Both long- and short-chain PFAS could migrate downwards to deep soil profiles but to varying extents, with the latter group transport deeper in soil profiles. The smallest-sized PFAS targeted in this study, perfluorobutane sulfonic acid (PFBS), was found to leach down even to the depth of 180 cm at one plot, indicating short-chain PFAS have a very high mobility and could contaminate the larger areas of agricultural land. The positive relationship was found between the total mass of PFOA and PFOS in soil profiles versus the cumulative loading rate of biosolids, indicating the continuous inputs of these two legacy PFAS compounds from the land-applied biosolids. The long-term repeated land applications of biosolids might result in the increased abundance of new PFAS in the soil with years such as PFBS, which could be due to the shifting PFAS composition in biosolids or the transformation of precursors with a long time.

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# Evaluation of Corncob Biochar Application on Soil Fertility, and Nitrogen Cycle

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**ABSTRACT**

*Coffea arabica* L. is a vital economic crop in the highland regions of Northern Thailand, but its sustainable production is increasingly threatened by soil degradation and climate change. This study aimed to assess the long-term efficacy of corn cob biochar application on critical soil parameters. We evaluated the effects on soil physical and chemical properties and the nitrogen (N) cycle by comparing the control to biochar application 12 months prior. The results indicated that biochar application significantly enhanced soil quality. Specifically, soil organic matter (SOM) increased by 5.35% compared to the control. The electrical conductivity (EC) reached a maximum of 74.0 ± 1.31 mg $kg^{-1}$ in the biochar application. Crucially, biochar improved exchangeable Potassium increased from 378.75 ± 7.25 mg $kg^{-1}$ in the control to 647.25 ± 1.87 mg $kg^{-1}$ in the biochar application, and exchangeable Magnesium was significantly higher in the biochar application (140.25 ± 0.53 mg $kg^{-1}$) compared to the control (49.20 ± 1.26 mg $kg^{-1}$). Regarding the N cycle, ammonium ($NH^{4+}$) levels were highest in the biochar application (51.12 ± 0.63 mg $kg^{-1}$), but were not significantly different from the control. However, the biochar application showed the highest nitrate ($NO_3^-$) level, reaching 114.54 ± 9.61 mg $kg^{-1}$. The results demonstrate biochar's potential as an effective and sustainable soil management strategy to enhance productivity and resilience for *Coffea arabica* L. production in vulnerable highland ecosystems.

**Keywords:** *Coffea arabica* L., Corncob biochar, Plant growth-promoting, Soil fertility, Sustainable agriculture

**Acknowledgments**

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# Fe(II) and Organic Acid Influence Arsenic Sorption by Magnetite

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**ABSTRACT**

Mitigating arsenic (As) contamination, a toxic metalloid, through magnetite adsorption is a promising remediation strategy. However, the effects of Fe(II) and organic acid release from rice roots on As sorption on magnetite are not fully understood. Herein, we investigated the effects of Fe(II) and acetic acid, as a model organic acid released from rice roots, on As(V) and As(III) sorption on magnetite. Kinetic results demonstrated that Fe(II) with or without acetic acid promoted a complete As(V) adsorption. Conversely, acetic acid alone lowered As(V) adsorption compared to the addition of Fe(II) or Fe(II) + acetic acid. Similar trends were observed in As(III) systems, where As(III) adsorption decreased, but oxidation of As(III) to As(V) increased. Our findings highlight the combined effects of Fe(II) and organic acids on As-magnetite interactions, with implications for As mobility at the soil-rice root interface under redox conditions.

**Acknowledgments**

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# Quantifying drivers of soil acidification under pakchoi cultivation with varying nitrogen inputs in Hainan, tropical China

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**ABSTRACT**

Soil acidification poses a significant challenge to global agricultural sustainability. In China, particularly in tropical regions like Hainan, soil acidification has worsened over recent decades, threatening crop productivity and ecosystem stability. However, the mechanisms driving soil acidification in this area remain poorly quantified.

This study employed a soil column-pot experiment based on the proton budget method to quantify the contributions of various acidification processes (N cycling, unbalanced crop uptake of anions and cations (crop uptake), direct proton input, mineral weathering/cation exchange, and anion desorption) in three typical soils in Hainan including volcanic latosol (WC), granite latosol (JA), alluvial paddy soil (JJ). Each soil was subjected to varying nitrogen levels (0, N0; 200 kg N $ha^{-1}$, N1) under pakchoi (*Brassica rapa*) cultivation.

The results (Figure 1) revealed that anion desorption was the dominant proton source (70%-90%) in the two latosols (WC and JA), while it contributed equally with crop uptake (45%-54%) in the paddy soil (JJ). The contribution of direct proton input was negligible (<0.1%). Mineral weathering and cation exchange were the primary buffering mechanisms, neutralizing 78–99% of generated protons across all treatments. Nitrogen transformation contributed to proton consumption in some treatments, particularly in WC-N1, where it accounted for 21%. Proton production and consumption were significantly influenced by soil type ($P< 0.01$), with JJ and JA soils showing higher proton flux compared to WC soil. Nitrogen fertilization significantly increased proton production and consumption in WC and JJ soils (P = 0.04 and P = 0.02, respectively), but had no significant effect on JA soil.

This study underscores that anion desorption and plant uptake, not N transformation, are the predominant acidification pathways in tropical vegetable systems in Hainan. These findings offer valuable insights for developing tailored soil management strategies to mitigate acidification in tropical agricultural systems.

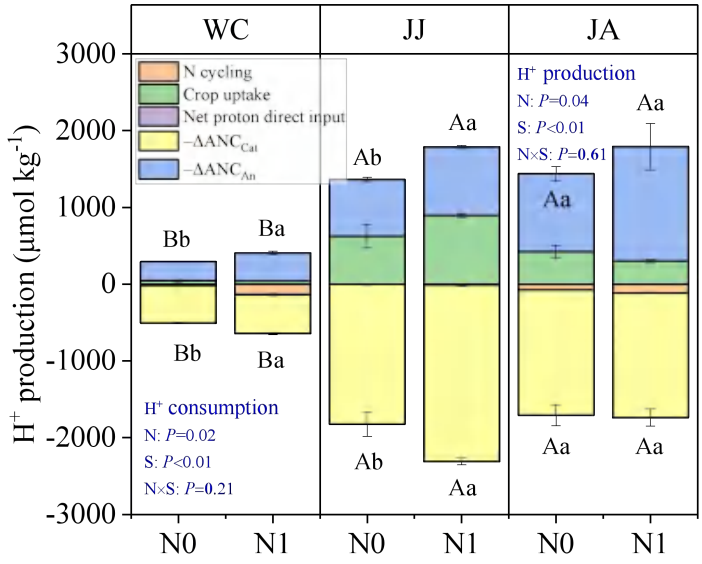



**Figure 1** Proton production/consumption under different treatments by different processes including nitrogen transformation (N Cycling), unbalanced crop uptake of anions and cations (crop uptake), net proton direct input, mineral weathering/cation exchange (-$\Delta ANC_{Cat}$), and anion desorption (-$\Delta ANC_{An}$). Positive and negative values indicate proton production and consumption, respectively. WC, JJ, and JA represent the three soils, and N0 and N1 indicate the treatments without nitrogen fertilizer and conventional nitrogen fertilization (200 kg N $ha^{-1}$), respectively. Uppercase and lowercase letters represent significant differences ($P< 0.05$) in proton production and consumption among different soil types and nitrogen application levels, respectively. Error bars indicate the standard error (SE, n = 3).

**Acknowledgments**

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# Abiotic Transformation of PFAA Precursors in Soil Under Environmental Conditions

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFAS) remain a major environmental concern due to their persistence and the continuous discovery of new precursor compounds in soil systems. While biotic pathways have been studied extensively, the role of soils in driving abiotic transformation of perfluoroalkyl acid (PFAA) precursors under environmentally relevant conditions is far less understood. This study investigates how common soil components—minerals, natural organic matter, redox-active species, and moisture regimes—facilitate or inhibit the chemical transformation of several representative precursors. The goal is to clarify the extent to which soils themselves act as reactive media capable of generating terminal PFAAs.

We conducted controlled laboratory experiments using well-characterized soils spanning a range of textures, organic carbon contents, and redox potentials. Precursors, including fluorotelomer sulfonates and polyfluorinated amides, were incubated under conditions that mimic moistures, wet-drying cycles, natural pH gradients, and oxygen-limited microenvironments. Over weeks to months, transformation products were quantified using high-resolution mass spectrometry. Reaction kinetics were evaluated alongside changes in soil physicochemical properties to identify key drivers of abiotic conversion.

We speculate that soil can promote slow but measurable transformation and degradation of precursors into shorter-chain PFAAs. Mineral surfaces-especially iron- and manganese-bearing phases-played a central role. These minerals participated in redox-mediated processes that altered precursor functional groups, resulting in stepwise defluorination or oxidation. Organic matter contributed both catalytically and through sorption-driven concentration of precursors at reactive interfaces. Moisture fluctuations were also crucial; periods of drying and rewetting produced transient chemical conditions that accelerated transformation in several soil types. However, transformation rates varied widely, underscoring the heterogeneity of real-world soils.

The study provides new evidence that abiotic processes in soils contribute to the environmental formation of persistent PFAAs. Although slower than microbial pathways, these reactions may operate continuously across large soil volumes and long timescales. As a result, abiotic transformation likely represents a non-negligible source of PFAA accumulation in terrestrial environments. Understanding these mechanisms is essential for improving fate models, assessing long-term risks, and designing more effective remediation strategies for PFAS-impacted sites.

# Molecular modeling of natural organic matter-heavy metal cations interactions

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**ABSTRACT**

Interaction between natural organic matters (NOM) and heavy metal cations in aqueous environment are of great significance for maintaining stability of organic carbon and restraining transport of heavy metal contaminants in (bio)geochemical processes. We systematically explore the aggregation process and complexation between NOM and heavy metal cations ($Ag^{+}$, $Cd^{2+}$, $Pb^{2+}$, $Zn^{2+}$, $Eu^{3+}$) under different pH condition by molecular dynamics (MD) simulations, umbrella sampling method, and quantum chemistry calculations. The character of molecular structures NOM-heavy metal complexes and association are quantified. In acidic pH condition, aggregation proceeds via H-bonding and π-π interactions between NOM fragments. In neutral condition, $Ag^{+}$, $Cd^{2+}$, $Pb^{2+}$, and $Eu^{3+}$ can form inner-sphere complexes with the surface carboxylic groups and therefore reduce intermolecular charge repulsion, eventually leading to NOM aggregation, and it shows that even without direct binding, the outer-sphere adsorbed $Zn^{2+}$ can also result in the formation of NOM assemble through H-bonding. Consequently, these heavy metals are capable of promoting NOM aggregation regardless of the complexing ways. Complexing free energy calculations characterized the dynamic processes of cations binding to the carboxylic groups of NOM fragment and the related energy landscape. This study provides quantitative insights for understanding the environmental processes of heavy metals and cycle of C in aquatic ecosystem, and contributes to developing environment-friendly strategies for controlling heavy metal contaminants.

**Acknowledgments**

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# Size-dependent colloidal stability and transport behaviors of typical zonal soil colloids

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**ABSTRACT**

Colloidal particles, the finest constituents of soil, originate from complex physicochemical interactions among clay minerals, metal oxides, and organic matter. Their environmental behavior plays a critical role in soil structure formation, solute transport, and soil genesis. As particle size decreases, changes occur in the composition of organic matter and clay minerals, as well as in surface properties and aggregation-migration behaviors. However, studies addressing the size-dependent surface characteristics and environmental behaviors of soil colloids remain limited. In this study, typical zonal soils from China—Phaeozem (black soil), Cambisol (brown soil), Luvisol (yellow-brown earth), and Ferralsol (latosol)—were selected. Colloidal fractions with diameters of $d$ < 2000 nm, $d$ < 1000 nm, $d$ < 500 nm, and $d$ < 100 nm were extracted through ultrasonic dispersion combined with high-speed centrifugation, and their composition, surface properties, and aggregation/migration behaviors were systematically analyzed. The results showed that, as particle size decreased, colloidal particles from Phaeozem, Cambisol, and Luvisol exhibited reductions in both diameter and thickness, while Ferralsol colloids showed minimal changes. The absolute value of the zeta potential initially increased and then decreased, indicating reduced surface charge variability. Soil organic carbon was predominantly enriched in finer fractions, particularly in nanocolloids ($d$ < 100 nm), which were characterized by a higher density of surface functional groups, greater aromaticity, and lower hydrophilicity. The critical coagulation concentration (CCC) of Phaeozem colloids decreased with decreasing particle size, while Cambisol colloids exhibited an initial decrease followed by an increase. In contrast, the CCC of Luvisol and Ferralsol colloids increased as particle size decreased. These variations in aggregation behavior were attributed to the balance between electrostatic repulsion and van der Waals attraction. The highest mobility was observed for the $d$ < 500 nm fractions of Phaeozem, Cambisol, and Luvisol colloids, and for the $d$ < 1000 nm fraction of Ferralsol colloids. Conversely, the weakest mobility was found in the nanocolloidal fractions of all soils, likely due to their lower absolute value of the zeta potential and higher densities of surface functional groups. The critical particle diameters controlling size effects were determined to be 500 nm for Phaeozem, Cambisol, and Luvisol colloids, and 1000 nm for Ferralsol colloids. These findings provide a theoretical foundation for more accurately assessing the environmental behavior of soil colloids and their roles in pollutant transport processes.

**Key words:** Soil colloids; Size-dependent behavior; Critical coagulation concentration; Mobility;

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# Soil–Plant Isotopic Coupling in Support of PDO Agri-Food Traceability

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**ABSTRACT**

Authentication and geographical traceability are essential to protect the quality and integrity of agri-food products with geographical indications. Stable isotope ratio analysis provides intrinsic markers of origin that reflect environmental conditions and agronomic practices during plant growth, offering a robust alternative to documentary traceability. The isotopic composition of light bioelements—carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and sulfur ($\delta^{34}S$)—captures soil–plant–atmosphere interactions and has proven effective in food authentication, although its application to tomato provenance remains limited.

This study investigates the potential of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ as tracers for the authentication and geographical discrimination of *Pomodorino del Piennolo del Vesuvio* (PPV) PDO. Tomato fruits and corresponding soils were collected over four growing seasons from farms located within and outside the PDO area and analysed by isotope ratio mass spectrometry (IRMS). Spatial and interannual variability were evaluated, and chemometric approaches were applied to assess discrimination performance.

Across the four years, interannual isotopic variability was limited and did not obscure the geographical signal. $\delta^{13}C$ values, consistent with $C_3$ plant physiology, showed moderate year-to-year variations mainly related to water availability, while $\delta^{15}N$ remained relatively stable. $\delta^{34}S$ displayed a progressive enrichment over time without compromising area discrimination. PDO tomatoes were characterized by higher $\delta^{13}C$ values, reflecting drier pedoclimatic conditions and rainfed cultivation on Vesuvian slopes, whereas non-PDO samples showed higher $\delta^{15}N$ and $\delta^{34}S$ values, likely linked to different fertilization practices and sulphur sources. Significant differences were also observed in elemental composition (C, N, S).

Multivariate analyses confirmed a clear separation between PDO and non-PDO samples. Principal Component Analysis highlighted $\delta^{15}N$ and $\delta^{34}S$ as primary discriminants, while Linear Discriminant Analysis achieved classification accuracies between 85% and 100% depending on the year, and approximately 84% for the combined dataset. No significant isotopic or elemental differences were found between PPV varieties, indicating that environmental and management factors outweigh genotypic effects. Soil isotopic data mirrored fruit signatures, and significant correlations between soil and tomato isotopic values further supported the soil–plant isotopic coupling.

Overall, the combined use of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$, integrated with chemometric tools and soil characterization, provides a robust and science-based framework for PDO agri-food traceability and the authentication of Vesuvian tomatoes.

**Acknowledgments**

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# Effects of Phosphogypsum on Heavy Metal Mobility and Nutrient Dynamics in Saline Soil under Spring Wheat

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## ABSTRACT

Phosphogypsum (PG), a low-cost by-product of the phosphate fertilizer industry, has received growing attention, particularly in regions with degraded soils. Despite its potential benefits, PG poses substantial environmental challenges due to its large-scale accumulation: around 7 billion tons have been stockpiled globally, although 80 million tons are produced annually and only 15–40% is currently utilized. PG can improve soil health by regulating pH, stabilizing aluminum compounds and enhancing soil structure. Additionally, it contains essential nutrients such as calcium, sulfur and phosphorus, making it a promising soil amendment and fertilizer.

This study evaluated the effects of PG application on soil chemical properties, nutrient availability, and heavy metal mobility in saline soil cultivated with spring wheat (*Triticum aestivum* L.). A two-year pot experiment was conducted under controlled greenhouse conditions. In the first year, PG was applied at rates of 2 and 10 t $ha^{-1}$. In the second year, residual effects were assessed without additional PG, while a separate set of pots received repeated applications at the same rates to evaluate cumulative impacts. Although the experiment spanned two years, the study focuses on the results from the second year. Soil samples were analyzed for toxic elements and heavy metals, including aluminum (Al), arsenic (As), barium (Ba), chromium (Cr), cobalt (Co), lead (Pb), and cadmium (Cd), as well as for essential nutrients (phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S) and sodium (Na)).

Residual effects of PG generally resulted in higher concentrations of Al, Ba, Cr, Co, Pb, and Cd than repeated applications, especially at 10 t $ha^{-1}$. Repeated applications produced mixed effects on these elements, occasionally reducing their levels to the control. As showed no response to both residual and repeated PG applications.

PG increased P, Ca, Mg, and S levels compared to the control, with higher doses producing more pronounced effects. Residual treatments mainly enhanced P and Mg availability, reflecting the slow release of phosphate and mobilization of native Mg. In contrast, repeated applications had a stronger effect on Ca accumulation, due to the cumulative addition of Ca. Sulfur enrichment occurred in both application types, owing to the sulfate content of PG. Sodium concentrations decreased under all PG treatments, likely through $Ca^{2+}$ displacement of $Na^{+}$ from exchange sites, indicating a potential ameliorative effect on saline soils.

Overall, PG improved nutrient availability while repeated applications tended to limit heavy-metal accumulation compared to residual effects, indicating that controlled, repeated PG use may enhance soil quality with lower environmental risk.

**Acknowledgments**

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# Iron-carbon coupling in salinized drylands

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**ABSTRACT**

Salinized arid regions harbor substantial yet fragile carbon pools and are experiencing multiple disturbances from intensive reclamation. Here we evaluate the response of iron-bound organic carbon (Fe-bound OC) to salinization and reclamation across a 1600-km transect in northwest China. Fe-bound OC averages 16.6% of soil organic carbon (SOC) in salt-affected natural vegetation areas but decreases with increasing salinity. Crystalline iron mineral phases, dominant in these areas, stabilize aromatic organic compounds through adsorption, with a shift to coprecipitation-dominated mechanisms post reclamation. Although reclamation increases Fe-bound OC and SOC contents, the limited availability of iron constrains iron-carbon coupling, resulting in a reduced Fe-bound OC contribution to SOC (12.7%). This finding highlights the potential to enhance net carbon sequestration during reclamation by strategically managing iron-carbon coupling. The complementary incubation experiments demonstrate that the tailored application of crystalline iron (oxyhydr) oxides offers a promising pathway to synergize carbon sink enhancement with agricultural productivity in salinized arid regions, thereby advancing climate-resilient land restoration.

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# Initial changes in soil microbial community structure after combined biochar and straw application to agricultural soil: evidence from a 180-day incubation experiment

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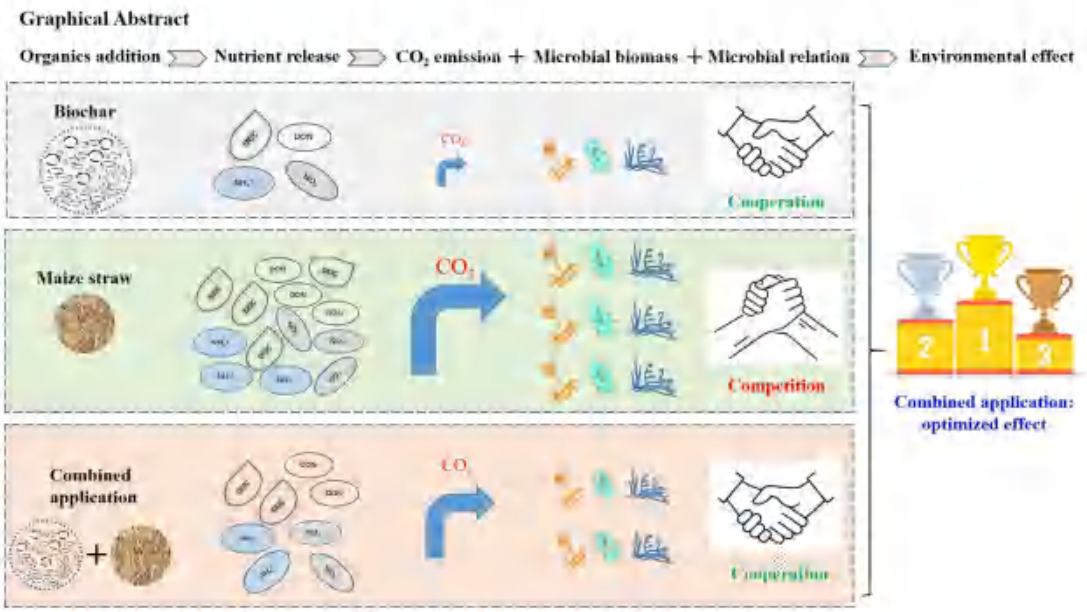
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## ABSTRACT

Organic amendments are applied to agricultural soils to maintain fertility and function. In the present study, we monitored the CO2 emissions and analyzed the microbial biomass, community structure, and network complexity under single and combined applications of maize straw and maize straw-derived biochar (550 °C, 2 h) during a 180-day incubation experiment. The cumulative $CO_2$ emissions were ordered straw > biochar + straw > biochar, and the $CO_2$ emissions in the biochar + straw treatment were 41%–51% lower than those of the straw-only treatment. The content of phospholipid fatty acids (PLFAs) was not affected by biochar but increased under straw ($p < 0.05$) and decreased by 1.9%–46% under the combined treatment compared with the straw-only treatment, suggesting that microorganisms had various demands for nutrients. The greatest effects of applying organic material on the microbial community were found at the end of incubation under biochar, but at the start of incubation under straw addition, based on the nutrient supply provided by the type of material input. Biochar + straw strengthened cooperation between microorganisms by enhancing network complexity and alleviating competition in the network structure. Therefore, biochar + straw had an optimized effect on mitigating CO2 emissions and stimulating microbial community development compared to straw-only.

## Graphical ABSTRACT



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# CONTROL AND EVALUATION OF ALUMINUM METAL COMPONENTS IN SALINE ACID SULFATE SOIL BY ECO-FRIENDLY AMENDMENTS

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## ABSTRACT

**Purpose**

Saline acid sulfate soil is a type of acid sulfate soil affected by seawater intrusion, characterized by both acid sulfate properties and salinity. This soil contains high concentrations of sulfides, which, upon oxidation, form sulfuric acid, further increasing acidity and releasing toxic elements such as aluminum (Al) and iron (Fe) into the soil solution. This study aims to utilize amendments such as lime (LM), cow manure (CM), husk biochar (HB), and their combinations to reduce Al fractions, thereby transforming them into more stable forms to mitigate soil toxicity for enhancing agricultural sustainability in these degraded environments.

**Methods**

A greenhouse incubation experiment was established with six treatments: control (no amendment), LM, CM, HB, HB+LM, and HB+CM applied under two water regimes (submerged and moist at 60% field capacity), each with four replications. Soil samples were analyzed for aluminum fractions using the single extraction method. The aluminum fractions include: Exchangeable aluminum ($Al_K$), Weakly organic-bound aluminum ($Al_{Cu}$), Strongly organic-bound aluminum ($Al_p$), Non-crystalline aluminum ($Al_o$), Crystalline aluminum ($Al_n$), Crystallizes tightly aluminum ($Al_n$-$Al_o$).

**Results**

In the submerged condition, $Al_{Cu}$ was highest in HB+CM (64.36 mg $kg^{-1}$) and lowest in HB+LM (49.93 mg $kg^{-1}$). $Al_p$ was greatest in the CM treatment (4,877 mg $kg^{-1}$) and lowest in HB+LM (4,414 mg $kg^{-1}$), indicating a strong Al-fixation capacity of CM under submerged conditions. $Al_o$ increased markedly in HB+LM (161.01 mg $kg^{-1}$). $Al_n$ and $Al_n$-$Al_o$ did not differ significantly among treatments. $Al_K$ was lowest in HB+LM (9.91 mg $kg^{-1}$) and highest in CM (17.42 mg $kg^{-1}$), demonstrating that LM, particularly when combined with HB, effectively reduced $Al_K$. Moist condition, $Al_o$ remained highest in HB+LM (175.38 mg $kg^{-1}$). $Al_K$ decreased with HB+LM (15.58 mg $kg^{-1}$), whereas the control maintained higher values. $Al_n$-$Al_o$ remained stable and was not affected by the amendments. Overall, submerged conditions amplified the differences among amendments, whereas at moist conditions, the HB+LM was particularly effective in increasing $Al_o$ and reducing $Al_K$.

**Conclusions**

The use of soil amendments such as LM, CM, HB, and their combinations (HB+LM and HB+MC) has proven effective in reducing the levels of $Al_K$ and $Al_{Cu}$. These amendments not only increase soil pH, promoting the precipitation of aluminum into insoluble forms, but also create organic bonds that transform aluminum ($Al_K$, $Al_{Cu}$, and $Al_p$) from more easily absorbed forms into less toxic forms such as $Al_o$ and $Al_n$. As a result, the toxicity of Saline acid sulfate soil is minimized, creating favorable conditions for plant growth.

**Keywords:** Aluminum metal components, amendments, biochar, water regimes

# Sorption and Desorption of Phosphorus in Soil: Implications for Water Quality

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**ABSTRACT**

In Norway, many agricultural soils are enriched in phosphorus (P), raising concerns about water quality. This issue is particularly pronounced on animal farms, where repeated manure applications have resulted in substantial soil P accumulation. Laboratory experiments conducted on a range of soils showed that leaching of dissolved P is strongly influenced by soil P sorption and desorption properties. In particular, the mass-weighted, whole-profile degree of P saturation determined using the ammonium lactate extraction method (DPS-AL) was found to be an excellent predictor of the flow-weighted mean concentration of total dissolved P (FWMC-TDP) (adjusted $R^2 = 0.93$, $p < 0.001$) (Liu et al., 2024). This strong relationship has important implications for assessing the risk of P leaching.

Within the EU Horizon-funded SOILPROM project, we aim to integrate this relationship into P modeling using the ICECREAM model. The modeling is based on a long-term monitored field site in southeastern Norway, where climate data and field management information have been collected since 1992, and P losses via both surface runoff and subsurface drainage were measured during 1992–2005. These long-term datasets provide a robust foundation for model calibration, validation, and predictive simulations. Results from both the laboratory experiments and the model simulations will be presented at the conference.

**Acknowledgments**

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# A high-resolution map of urban soil pH in the megacity of Xi'an

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**ABSTRACT**

Soils contain the largest pool of terrestrial carbon, and thus significantly influence climate change either by releasing $CO_2$ under industrial cropping, or by sequestrating carbon with conservation practices, yet the role of urban soils in the global carbon cycle is poorly known. Since urban areas contribute over 70% of global greenhouse gas emissions due to dense, anthropogenic pollutant-emitting activities (UN-Habitat, 2011), we hypothesized that the physico-chemical properties of soils could be altered by higher atmospheric $CO_2$ concentrations. There is also a lack of high-resolution urban maps of soil pH, because published literature reports only estimations based on digital modeling with few real data (Suleymanov *et al.*, 2025). Here, we studied the pH of 192 soils sampled near the city center in three block of increasing urbanization, and in natural surroundings of Xi'an, a megacity of 9.2 millions inhabitants. We also measured atmospheric $CO_2$ levels. Results show statistically significant soil pH differences with degrees of urbanization and pollution, suggesting $CO_2$-induced soil acidification. We also present the first high-resolution (50 m) map of soil pH in a megacity.

**Keywords:** $CO_2$ concentrations, urban soil, pH

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# High resolution mapping of carbon dioxide pollution in the Xi'an megacity, using plant carbon isotopes

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**ABSTRACT**

The acceleration of global warming is calling for reducing fossil $CO_2$ emissions, yet the sources and spatial distribution of $CO_2$ are still poorly known, notably in urban areas, which contribute over 70% of global greenhouse gas emissions due to dense, anthropogenic pollutant-emitting activities (UN-Habitat, 2011). While the occurrence of $CO_2$ domes have been evidenced at the whole city scale (Idso et al. 2013), the long-term distribution of atmospheric $CO_2$ levels at block and road scales remains unknown. In particular, it is not known whether fossil $CO_2$ is homogeneously mixed by the traffic-induced city local winds, or remains concentrated in some specific urban areas. Here we studied one year of local fossil $CO_2$ pollution by analyzing the 374 samples of plant leaves from four species, taken at 50 m distance in three Xi'an blocks, and in natural areas as control. Fossil fuel carbon was distinguished using bulk and molecular $^{13}C$ analysis (Lichtfouse and Eglinton, 1995, Lichtfouse et al. 2003), and we modeled city winds at the local scale. Results show striking differences in fossil carbon ratio with the occurrence of '$CO_2$ islands', proving that $CO_2$ is not homogeneously mixed by city winds, suggesting protective effects of urban vegetation, e.g. trees, and of urban infrastructure, e.g. 30-stories buildings. Molecular isotope analysis allowed to exclude the possible contribution of airborne fossil fuel hydrocarbons, which is supported by the high combustion efficiency of actual vehicle engines and by the fast increase of the number of electric vehicles. Overall, these findings represent the first high resolution map of fossil carbon pollution in a city.

**Keywords:** Megacity, $CO_2$ concentrations, plant, $^{13}C$, *n*-alkanes

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# Contact-Electro-Catalysis at the Iron Mineral–Water Interface: A New Abiotic Source of Environmental ROS

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**ABSTRACT**

Reactive oxygen species (ROS) are critical agents driving elemental biogeochemical cycles and the transformation of pollutants in Earth's surface environments. Conventionally, abiotic ROS generation has been predominantly attributed to photochemical reactions and transition metal-catalyzed Fenton-like processes. Recently, growing attention has been paid to contact electrification at water-solid interfaces and its role in initiating physicochemical processes. Electron transfer during water-solid contact can drive chemical reactions, a mechanism known as contact-electro-catalysis (CEC). As a novel catalytic process powered by mechanical energy, CEC has been demonstrated to effectively generate ROS at solid-liquid interfaces. However, its significance and mechanisms in natural settings involving key reactive minerals, such as iron oxides, remain poorly understood. This study investigated the possibility and mechanistic pathways of ROS production via CEC at the interface between iron minerals and water. Our experimental results confirmed that contact electrification occurred between iron minerals and water with further indeed induced ROS generation. Notably, unlike the CEC pathways reported for polymeric materials, we discovered that ROS generation in this mineral system proceeded primarily through a synergistic mechanism. This mechanism involved an initial CEC step that subsequently activates and couples with surface Fenton-like reactions on the mineral. In this process, surface functional groups of iron minerals are pivotal in governing this interfacial CEC process. Furthermore, experiments conducted under simulated environmental contact conditions substantiated that CEC to contributes to ROS generation in natural scenarios. In summary, this work provided the first systematic elucidation of ROS generation via CEC at iron mineral-water interfaces, implying the catalytic potential of common iron minerals in soil under natural mechanical action. It provides a new pathway and perspective for abiotic ROS formation in the soil environments and offers a novel theoretical framework that advances the fundamental understanding of soil environmental ROS sources.

**Key words:**Iron mineral; Contact-electro-catalysis; Reactive oxygen species; Water-solid interface

# Emerging Contaminants in Soil, Water, and Plant Systems: One Health Perspective

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**ABSTRACT**

Mitigation of emerging contaminants in soil, water, and plant systems is critical to protecting agriculture, ecosystems, and human health. One Health approach is needed to address the new threats posed by environmental emerging contaminants through interdisciplinary research. This presentation highlights our recent studies: 1) antibiotics, bacterial communities, and antibiotic resistance genes in vegetables upon antibiotic exposure; 2) sorption and internalization of silver nanoparticles by plants and effectiveness of vegetable washing procedures; 3) study and management of the entire metal(loid)s (metallome) in carrot and wheat as influenced by soil water conditions, plant growth stages, and soil amendment application; 4) training machine learning models to predict the uptake and accumulation of per- and polyfluoroalkyl substances (PFAS) by crops; 5) simulating interactions of prion fibrils between metal ions or model geosorbent surfaces using molecular dynamics. These studies can improve our fundamental understanding on environmental processes and impacts of emerging contaminants and further help us develop scientifically-sound mitigation and management strategies.

**Acknowledgments**

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# Microbial potential to mitigate neurotoxic methylmercury accumulation in farmlands and rice

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**ABSTRACT**

Toxic methylmercury ($CH_3Hg^+$) is produced by microbial conversion of inorganic mercury in hypoxic environments such as rice paddy soils, and can accumulate in rice grains. Although microbial demethylation has been recognized as a crucial pathway for $CH_3Hg^+$ degradation, the identities of microbes and pathways accountable for $CH_3Hg^+$ degradation in soil remain elusive. Here, we combine $^{13}CH_3Hg^+$-DNA stable-isotope probing experiments with shotgun metagenomics to explore microbial taxa and associated biochemical processes involved in $CH_3Hg^+$ degradation in paddy and upland soils. We identify *Pseudarthrobacter*, *Methylophilaceae* (MM2), and *Dechloromonas* as the most significant genera potentially engaged in the degradation of $^{13}CH_3Hg^+$ in paddy soil with high mercury contamination. We confirm that strains affiliated with two of those genera (species *Dechloromonas denitrificans* and *Methylovorus menthalis*) can degrade $CH_3Hg^+$ in pure culture assays. Metagenomic analysis further reveals that most of these candidate $^{13}CH_3Hg^+$ degraders carry genes associated with the Wood-Ljungdahl pathway, dicarboxylate-hydroxybutyrate cycle, methanogenesis, and denitrification, but apparently lack the *merB* and *merA* genes involved in $CH_3Hg^+$ reductive demethylation. Finally, we estimate that microbial degradation of soil $CH_3Hg^+$ contributes to 0.08-0.64 fold decreases in $CH_3Hg^+$ accumulation in rice grains across China (hazard quotient decrements of 0.62%-13.75%). Thus, our results provide insights into microorganisms and pathways responsible for $CH_3Hg^+$ degradation in soil, with potential implications for development of bioremediation strategies.

# Comparison for colloidal stability and aggregation behavior of fulvic and humic acids: effects of cations and pH

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**ABSTRACT**

Fulvic acid (FA) and humic acid (HA) are organic materials that can form complexes with metal ions, playing a crucial role in predicting the behavior of organic colloids. The colloidal stability values of FA and HA vary with pH and specific cations, but this has rarely been comprehensively examined. This study systematically compared the aggregation kinetics and colloidal stability of FA and HA and the mechanisms behind their behavior based on particle interaction theory. The results showed that higher pH values stabilized FA and HA colloids by increased electrostatic repulsive energy. Additionally, increased electrolyte concentration destabilized FA and HA colloids by cationic polarization (chemical bond formation). The cation aggregation ability followed the order $Ca^{2+}$ > $Mg^{2+}$ > $K^{+}$ > $Na^{+}$, showing that the specific ion effects induced by nonclassical polarization resulted from the strong electric field of the highly negatively charged FA and HA. With pH values ranging from 5 to 7 and 9, FA and HA were stabilized through raising the critical coagulation concentrations (CCCs) in NaCl and KCl. With increasing pH, the enhanced electrostatic repulsive energies in the Na+ and K+ systems resulted in weaker aggregation behaviors due to the deprotonation of the hydroxyl and carboxyl groups of colloids. Compared with HA, FA had a lower Hamaker constant, higher surface negative charges, larger CCCs, and stronger dispersion stability. This work will contribute to the understanding of organic colloidal aggregation mechanisms and act as a References to predict their environmental behaviors.

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# The fate of endocrine disruptor compounds in soil. The role of humic substances

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**ABSTRACT**

Endocrine disruptor compounds (EDCs) are hormone-like substances that include natural and synthetic estrogens and several pesticides, industrial chemicals, and plastic and pharmaceutical products and byproducts, which are able to alter, i.e., disrupt, the normal endocrine functions in humans and animals. These compounds may enter the soil through current agricultural practices and/or disposal of urban and industrial effluents, sludges and wastes. The estrogenic risk of EDCs is generally related to their distribution and speciation in the various soil phases, in which adsorption/desorption processes play a very important role. Humic substances, particularly their humic acid (HA) fractions, are universally acknowledged to be among the most chemically and biologically reactive components of soil. In this work, adsorption kinetics and adsorption/desorption isotherms of the EDCs bisphenol A (BPA), octyl-phenol (OP), 17-alpha-ethynyl estradiol (17ED) onto HA samples isolated from the surface (0-30 cm) and subsurface (30-90 cm) horizons of two sandy soils were determined using a batch equilibrium method and high performance liquid chromatography (HPLC).

The adsorption kinetics of EDCs by HAs was clearly distinguished in two phases, a rapid one in the first few hours (h) of contact, which corresponded to more than 90% of the total amount adsorbed, and a slow one that needed generally less than 24 h to be completed. Experimental adsorption data were best fitted in a Langmuir-type isotherm for BPA and 17ED, in a linear isotherm for OP, and in a non-linear, L-shaped Freundlich isotherm for EED. These results indicated that no limiting adsorption/saturation occurred for EED and OP onto the HAs examined over the concentration range tested, whereas a maximum adsorption, i.e., saturation, was reached by BPA and 17ED. In general, the HAs isolated from surface soils exhibited a much larger adsorption capacity for any EDC examined than that of HAs isolated from subsurface soil. The extent of adsorption of BPA was generally smaller than that of the other three EDCs, which were adsorbed at almost the same extent. The adsorption of EED, and especially of BPA, onto HAs was generally reversible, with desorption occurring quickly and almost completely after few desorption steps. On the contrary, adsorption of OP was almost irreversible, with partial desorption occurring slowly, and high amounts of OP retained by most HAs at the end of the experiment. The desorption was not studied for 17ED.

In conclusion, the soil HAs examined in this work were able to adsorb variable amounts of the four EDCs studied that would tend to accumulate in the soil surface horizon. However, BPA and EED could be quickly and completely desorbed, so these EDCs can be expected to move downward in the soil profile, which implies a serious risk of contamination of groundwater. Differently, OP was slowly and only partially desorbed, thus it can be expected to remain mostly adsorbed by HAs, especially on the surface soil layer, leading to the risk of a corresponding, more or less permanent top soil contamination.

**Acknowledgments**

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# Plant-Microbe Interactions Mediate Nitrogen Deposition Effects on Soil Carbon Cycling in a Desert Steppe Ecosystem

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**ABSTRACT**

In the context of globally increasing nitrogen (N) deposition, understanding how N inputs affect carbon (C) cycling in vulnerable ecosystems through plant–microbe interactions is essential for accurately predicting the carbon budget of terrestrial ecosystems. Dryland ecosystems, such as desert steppes, are particularly sensitive to exogenous N inputs due to their inherently low nutrient availability and fragile ecological structure. However, the mechanisms through which N deposition modulates belowground C processes—especially via changes in root exudation and associated microbial activity—remain inadequately understood. This study focuses on a desert steppe ecosystem, with the overarching aim of deciphering the "plant–microbe interaction" pathway through which N deposition influences soil organic carbon (SOC) transformation. Specifically, we investigate how N-induced shifts in the chemical composition of root exudates drive functional changes in rhizosphere microbial communities and subsequently alter the dynamics of SOC components. Methodologically, we employ an integrated multi-omics and soil biogeochemical approach. Root exudates are characterized using untargeted metabolomics to reveal their chemical diversity and compositional changes under N enrichment. These metabolic profiles are then correlated with key plant functional traits and soil abiotic factors (e.g., pH, available N, moisture). In the rhizosphere soil, we measure the activities of key hydrolytic and oxidative enzymes involved in C and N cycling. High-throughput sequencing of bacterial and fungal communities, coupled with functional gene quantification, is used to assess shifts in microbial taxonomic composition and functional potential. Furthermore, soil C fractions—including particulate organic C (POC) and mineral-associated organic C (MAOC)—are quantified to evaluate changes in SOC stability and turnover. By synthesizing data from root exudate metabolomics, microbial community and functional analyses, and soil C fractionation, this research aims to systematically unravel the cascading mechanism of "root exudates → microbial community structure/function → SOC transformation" in desert steppes subjected to N deposition. The study is expected to provide novel insights into the biochemical and microbial linkages that mediate ecosystem C responses to N enrichment.

# Effects of Microplastic Pollution on Soil Organic Carbon Turnover

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**ABSTRACT**

Microplastics (MPs, <5 mm) are recognized as an emerging contaminant in terrestrial ecosystems. MPs can directly influence soil organic carbon (SOC) turnover by serving as a carbon source and altering soil physicochemical properties. They also indirectly modify carbon cycling by influencing nutrient supply, microbial communities and functions, faunal ecological roles, and plant growth. Here, we investigated the relationships between MPs pollution and SOC turnover. A two-year-long field experiment showed opposite effects of conventional microplastics and biodegradable microplastics on plant residue decomposition. Conventional microplastics inhibited microbial biomass carbon and enzyme activities and reduced decomposition, while biodegradable microplastics increased soil nutrient levels, supported soil microbes and improved microbial diversity, and promoted decomposition. Another six-month soil microcosm experiment confirmed that MPs, particularly the non-biodegradable type, shifted soil aggregates from macro- to microaggregates, reduced aggregate stability, increased light fraction organic carbon, and promoted SOC transformation. In addition, $CO_2$ emissions were higher in MPs treatments than in controls, and $\delta^{13}C$ isotope tracing showed that priming effects were increased with both aggregate size and MPs concentration. Overall, MPs reshape SOC turnover through combined effects on soil aggregates and soil microorganisms, and conventional and biodegradable MPs show contrasting impacts.

**Keywords:** microplastics, soil organic carbon, soil aggregates

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# Sulfur Dynamics Coupled with Heavy Metal Behavior under Fluctuating Redox Conditions in Paddy Soils

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**ABSTRACT**

Intermittent irrigation, commonly known as alternate wetting and drying (AWD), is widely promoted in paddy fields to mitigate methane emissions. AWD induces fluctuations between reducing and oxidizing states in soils, which can reorganize the coupled cycling of sulfur (S) and heavy metals (HMs). While recent studies have shown that microbial activity in reduced paddy soils promotes the formation of $Cu_2S$ via biologically mediated sulfide production (Xu et al., 2023), the oxidation pathways of $Cu_2S$ following the disturbance of reducing conditions remain unresolved, particularly during brief oxygen exposure. This study aimed to elucidate the early-stage oxidation pathway of $Cu_2S$ in reduced paddy soils and to determine whether this process proceeds beyond sulfide minerals toward sulfate formation.

Three Japanese paddy soils (Brown Lowland soils, Gray Lowland soils, and Gley soils) were incubated under flooded conditions to establish reducing environments. After reduction was confirmed by redox potential (Eh) measurements, brief oxygen bubbling was applied to induce a transient oxidation event, followed by re-establishment of flooded conditions. During incubation, plant-available S and 0.1 M HCl-extractable HMs as a labile pool of HMs in the soils were quantified. Additionally, solid-phase Cu speciation was identified using Cu K-edge X-ray absorption near-edge structure (XANES) analysis.

Under reducing conditions, plant-available S and 0.1 M HCl-extractable Cu decreased markedly, indicating Cu immobilization as sulfide minerals. Subsequent short-term oxygen bubbling caused a clear increase in 0.1 M HCl-extractable Cu, whereas plant-available S showed no recovery, indicating negligible sulfate production. This asymmetric response suggests that $Cu_2S$ was not oxidized to sulfate but was partially transformed into CuS during the short-term oxidation. Cu K-edge XANES analysis confirmed the formation of CuS following transient oxidation, demonstrating that oxidation proceeded only to an intermediate sulfide phase.

Given the extremely short duration of the oxidation treatment, the observed $Cu_2S$-to-CuS transformation is best explained by initial abiotic oxidation rather than microbially mediated processes. Importantly, this reaction pathway—partial oxidation of $Cu_2S$ to CuS without re-oxidation of sulfide to sulfate—has not been previously reported in paddy soils. These findings reveal a previously unrecognized early-stage oxidation mechanism of copper sulfides under fluctuating redox conditions and provide new insight into Cu stability and transformation in reduced soil environments.

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# Soil Biological Crusts as Key Regulators of Surface Geochemistry in Degraded Semi-Arid Landscapes

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## ABSTRACT

Desertification is one of the most critical environmental degradation processes in semi-arid regions, leading to vegetation loss, enhanced erosion, and profound changes in surface soil geochemistry. In this context, soil biological crusts (SBCs) play a crucial role in protecting the soil surface and regulating the availability of metals and nutrients, particularly in degraded areas with sparse vegetation cover. This study aimed to evaluate the influence of SBCs on the accumulation and distribution of iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and phosphorus (P) in areas exhibiting different degradation levels within the Médio Jaguaribe Desertification Nucleus, Ceará State, Brazil.

A total of 70 paired samples of surface soil (0–10 cm) and SBCs were collected across three representative areas: degraded, recovering, and References (non-degraded). Concentrations of Fe, Mn, Zn, and Cu were determined by atomic absorption spectrometry, phosphorus by molecular spectrophotometry, and pH by potentiometric methods. Differences in metal and phosphorus concentrations between soils and SBCs within each area were assessed using Student's *t*-test or the non-parametric Mann–Whitney test, according to data distribution.

Higher accumulation of Mn and P in SBCs compared to adjacent soils was observed in all areas, with statistically significant differences consistently associated with higher concentrations in the crusts. These results highlight SBCs as effective surface compartments for retaining these elements. In the degraded area, SBCs exhibited substantially higher concentrations of Zn and Cu than the underlying soil, indicating that under conditions of severe degradation and low plant cover, SBCs play a central role in metal immobilization. This retention, mediated by Fe and Mn oxides and organic substances present in SBCs, contributes to reducing phosphorus losses via erosion and leaching, thereby enhancing nutrient cycling in degraded, phosphorus-poor environments.

In landscapes with low plant density, SBCs fill critical ecological gaps at the soil surface, assuming essential geochemical regulatory functions. Overall, SBCs demonstrate a high capacity to immobilize metals and phosphorus in disturbed environments, particularly in degraded areas, confirming their direct influence on surface soil geochemical dynamics in desertification-prone regions.

**Keywords:** Desertification; soil health; geochemistry.

**Acknowledgments**

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# Surface-Modified Carbonaceous Media for Enhanced Removal of Short-Chain Per- and Polyfluoroalkyl Substances from Urban Stormwater

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFAS) in urban stormwater represent a persistent environmental and public health concern, particularly for short- and ultrashort-chain compounds that are not effectively removed by conventional treatment technologies. This study evaluates the performance of surface-modified carbonaceous sorbents designed to improve the removal of short-chain PFAS in stormwater biofiltration systems. Two classes of modified carbonaceous materials were investigated: carbon materials functionalized with nitrogen-containing surface groups and biochar modified through the incorporation of metals.

Eight short- and ultrashort-chain PFAS were selected as target compounds, including perfluorobutanoic acid (PFBA), perfluorobutanesulfonic acid (PFBS), perfluoropentanoic acid (PFPeA), perfluoropentanesulfonic acid (PFPeS), perfluoropropanoic acid (PFPrA), perfluoropropanesulfonic acid (PFPrS), trifluoroacetic acid (TFA), and trifluoromethanesulfonic acid (TFMS). These compounds span carbon chain lengths from one to four carbons and include both carboxylate- and sulfonate-terminated functional groups. Nitrogen functionalization was achieved through covalent grafting of cationic nitrogen-containing moieties (i.e., quaternary ammonium and pyridine) onto carbon surfaces, while metal incorporation into biochar was used to introduce additional electrostatic attraction. Sorbent performance was assessed using batch adsorption experiments and continuous-flow column studies representative of engineered stormwater media filters. A one-dimensional intraparticle pore diffusion model was applied to both modified and unmodified carbonaceous materials, with model parameters estimated from experimental breakthrough data and used to predict full-scale filter performance under idealized operating conditions.

Results showed that PFAS chemical structure, including carbon chain length and terminal functional group, strongly influenced removal behavior across all materials. Nitrogen-functionalized activated carbon exhibited enhanced adsorption kinetics and higher adsorption capacity relative to unmodified materials, particularly for sulfonate-containing PFAS, consistent with improved external mass transfer and accelerated pore diffusion. Metal-incorporated biochar provided additional PFAS retention benefits. Sorption data were best fitted by the Freundlich isotherms for most target compounds. Column experiments demonstrated that modified carbonaceous materials substantially delayed PFAS breakthrough compared to unmodified media, and model simulations predicted multi-fold increases in filter lifetime. Collectively, these results indicate that surface modification of carbonaceous media through nitrogen functionalization and metal incorporation is an effective strategy for improving short- and ultra-short chain PFAS removal and extending the operational lifespan of stormwater treatment filters.

**Keywords:** Per- and polyfluoroalkyl substances; stormwater treatment; nitrogen-functionalized carbon; metal biochar

# Diurnal Formation and Influence Mechanisms of Multi-interface Reactive Oxygen Species in a Paddy System

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**ABSTRACT**

Changing redox conditions in paddy system, influenced by water, fertilizer, and photothermal processes, lead to high reactive oxygen species (ROS) production, which affects soil pollutant transformation. Studying ROS at the soil-redox interface is challenging due to their reactivity, diversity, and short lifespan.

In this study, we conducted rice potting experiments to quantitatively identify and spatially portray the dynamic processes involved in ROS formation across multiple interfaces—namely the overlying water, soil-water interface, and soil layer—within paddy systems during diurnal cycles. We employed techniques such as real-time molecular probe capture, in situ imaging using fluorescent films, and machine-learning modeling.

Our findings revealed that the generation of ROS within the paddy system's overlying water and at the soil-water interface reached its zenith during 13:00-15:00, delineating a daily pattern marked by pronounced peaks at noon and comparatively diminished levels in the morning and evening hours. The spatial distribution pattern for ROS production was identified as follows: soil-water interface > soil layer > overlying water; under different weather scenarios: sunny day > rainy day > cloudy day. Importantly, exogenous oxidative deposition substances such as hydrogen peroxide ($H_2O_2$) and rainfall inputs into the paddy system were found to significantly enhance ROS production ($p < 0.05$). Furthermore, illumination, temperature, Eh, and exogenous $H_2O_2$ inputs exhibited highly significant positive correlations ($p < 0.05$) with ROS levels within the paddy system; notably, illumination emerged as a key abiotic factor influencing ROS formation. Additionally, soil ROS act as a microbial metronome, transducing weather cues to orchestrate microbial community assembly.

The results of this research elucidate the mechanisms underlying ROS formation at multiple interfaces in paddy system throughout diurnal cycles while providing a theoretical foundation for a deeper understanding of environmental impacts associated with ROS dynamics in these agricultural systems.

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# Rice Growth and Yield Formation in Heterogeneous Sodic and Saline-Sodic Soils: Challenges and Management Strategies

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**ABSTRACT**

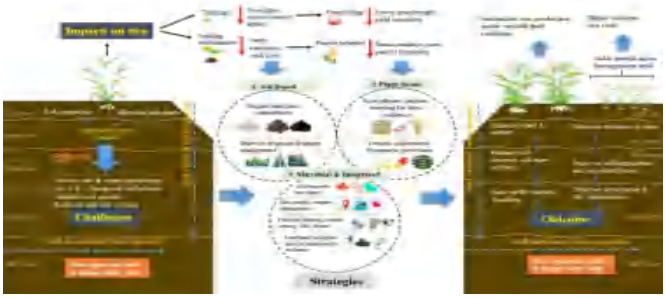
Soil salinity, sodicity, and alkalinity are frequently intensified by field-scale heterogeneity characterized by uneven spatial distribution of salts, moisture, and nutrients. In rice systems under sodic, saline-sodic soil conditions, such heterogeneity leads to uneven crop stands, variable plant responses, and challenges in applying uniform management practices. Worse, such fields receive different amounts of amendments, while similar field management practices are frequently supplemented, reducing the efficiency of amelioration. Meanwhile, field operations such as land leveling and ploughing further redistribute salts, probably creating new heterogeneity patterns. Currently, traditional methods fail to address these complexities, resulting in inconsistent growth, inefficient resource use, and variable yields. Despite these challenges, no systematic review has addressed them. This review fills the gap by examining how spatial variability in physico-chemical and biological factors affects rice performance at critical growth stages. It also evaluates integrated strategies, including organic/inorganic amendments, irrigation and drainage, and rice varieties and their cultivation to improve rice productivity under these conditions. Our review suggests focusing on the interaction between soil heterogeneity and plant growth, and on integrating plant- and soil-based management strategies with site-specific technologies, with particular focus on the critical growth stages of rice, where targeted interventions can significantly and effectively enhance rice performance in heterogeneous sodic/saline-sodic soils.

**Keywords:** Rice (*Oryza sativa* L.); soil heterogeneity; salinization; sodification; growth; yield.

**Conflicts of Interest**

The author showed no conflicts of interest.

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# Machine learning-based prediction of phenanthrene accumulation and toxicity in earthworms across soils

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**ABSTRACT**

Phenanthrene (PHE), a representative polycyclic aromatic hydrocarbon, readily bioaccumulates in soil organisms and poses substantial ecological risks. However, accurately predicting PHE toxicity across heterogeneous soils remains challenging due to complex soil-organism interactions. In this study, a machine learning (ML) framework was developed to predict PHE toxicity. Laboratory toxicity assays in 24 typical Chinese soils revealed a strong linear relationship between internal concentration ($C_e$) of PHE and earthworm fecundity, described by linear regression (LR). A comprehensive database encompassing soil physicochemical properties and PHE concentration ($C_s$) was constructed to support $C_e$ prediction. Among 11 ML algorithms evaluated, CatBoost exhibited superior performance ($R^2$=0.8), identifying $C_s$ as the primary determinant of $C_e$, followed by key soil properties (pH, soil organic matter). The integrated CatBoost-LR model accurately predicted toxicity ($R^2$=0.81) within external verification and enabled spatial assessment of PHE-associated ecological risks across China. These findings demonstrated that ML can quantitatively link soil properties to pollutant bioaccumulation and toxicity, providing a powerful, data-driven tool for ecological risk assessment of organic contaminants in complex terrestrial environments.

**Acknowledgments**

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# Selected forms of potassium in soils of the steppe and desert zones of Mongolia

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**ABSTRACT**

This study presents the results of research on the content of different potassium forms and the relationships between them in soil samples collected from 13 soil profiles located in Mongolia. According to the WRB soil classification system, the analyzed soils were classified into seven soil groups: Calcisols, Solonetz, Cambisols, Umbrisols, Kastanozems, Chernozems, and Phaeozems. The following forms of potassium were determined in the soil samples: water-soluble potassium, active potassium extracted with 0.01 mol·dm$^{-3}$ $CaCl_2$, plant-available potassium determined using the CAL method, exchangeable potassium extracted with 1 mol·dm$^{-3}$ $NH_4HCOO$, weakly fixed potassium extracted with 2 mol·dm$^{-3}$ HCl, strongly fixed potassium extracted with 1 mol·dm$^{-3}$ $HNO_3$ under hot conditions, reserve potassium extracted with 20% HCl under hot conditions and total potassium determined by digestion in a mixture of HF and $HClO_4$. The analyzed soil samples from profiles located in the desert and steppe zones of Mongolia were characterized by high contents of all analyzed potassium forms. The surface horizons of the analyzed soils were classified as having medium to very high potassium status. The highest accumulation of all studied potassium forms was observed in the surface horizons of the analyzed soil profiles. The content of the analyzed potassium forms followed the following increasing sequence: K-$H_2O$ < K-$CaCl_2$ < K-CAL < K-2M HCl < K-1M $HNO_3$ < K-20% HCl < K-HF.

The fixed potassium content in the analyzed soil samples was high and, on average, was three times higher than the exchangeable potassium content.

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# Ultrasensitive detection of trace Hg(II) in acidic conditions using DMABR loaded on sepiolite: Function, application and mechanism studies

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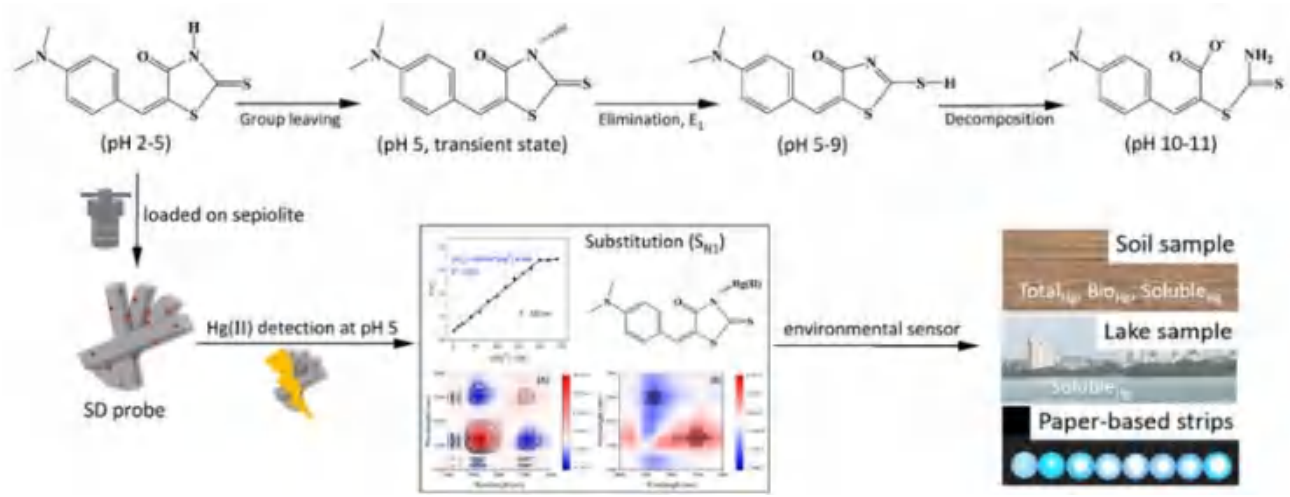
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## ABSTRACT

Fast and real-time detection of trace Hg(II) by fluorescent probes under acidic conditions is urgently required due to the high toxicity and accessibility to creatures and human being. However, fluorescent probes for Hg(II) detection in environmental samples are rarely reported due to the protonation potential of acidic mercury sources. In this study, the SD probe was developed by 5-(p-dimethylaminobenzylidene) rhodanine (DMABR) loaded on sepiolite by hydrothermal treatment, and showed excellent Hg(II) detection performances for mercury sources at pH 4–10 due to buffering ability of the hyperconjugated lactam rings. Sepiolite functioned as the support skeleton to decrease intermolecular transition, and thus increased the sensitivity. At pH 4, the SD probe showed high selectivity and sensitivity for Hg(II) among various species, with low LOD and binding constant of $4.78 \times 10^{-9}$ M and $1.34 \times 106$ $M^{-1}$, respectively. Through DFT calculations, MAS $^{1}$H NMR and 2D-COS analysis, the detection mechanism was demonstrated as $SN_1$ substitution of the spontaneous leaving H on amino groups in the transient state during tautomeric equilibrium, rather than the expected high-affinity sulphydryl. Additionally, the SD probe exhibited promising potential in quantifying water-soluble and bioavailable Hg(II) in acidic polluted soil and water samples. Moreover, real-time detection was realized by paper-based strips.




**Acknowledgments**

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# Novel Ball-Milled Tourmaline-Biochar Composite: Application in Heavy Metal-Contaminated Groundwater and Bottom Sediment Remediation

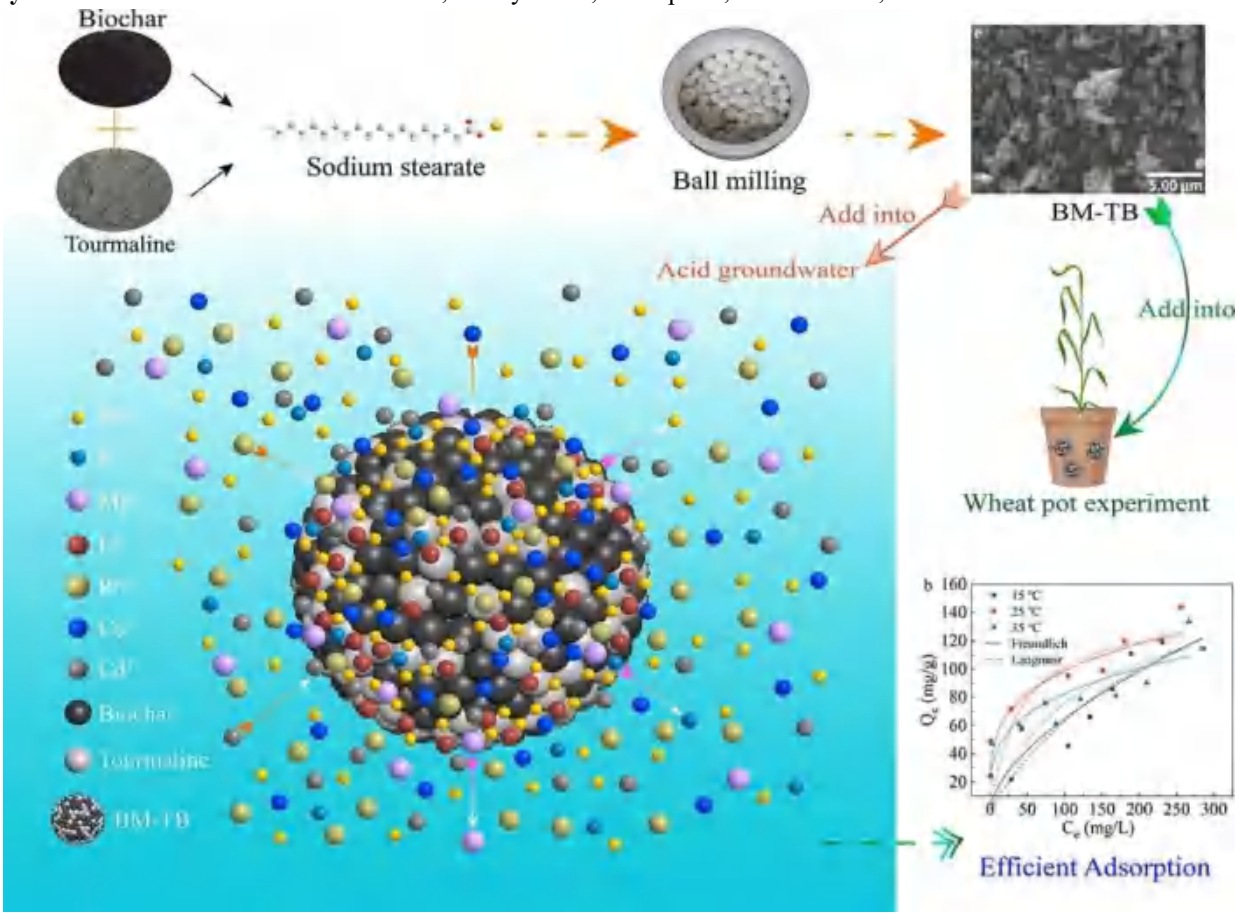
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**ABSTRACT**

A novel composited material of ball-milled tourmaline-biochar (BM-TB) developed have a good adsorption capacity for heavy metal in the wider pH ranges of the aqueous solution. The adsorption capacity of BM-TB for $Cd^{2+}$ was 142.6 mg/g when the solution pH was 4.0, and when pH was higher than 4.0. When the BM-TB was used to adsorb As, Cd, Cu and Pb from the groundwater, the adsorption percentage obtained 17.4 %, 93.6 %, 64.1 % and 95.9 %, respectively. When the BM-TB was used to remediate the soil, BM-TB can the can significantly reduce the bioavailability of Cu, Cd, Pb, Zn and As and inhibit their enrichment into plant. Additionally, the novel material was remediated the soil, it can amend the bottom mud and enhance the content of dissolved inorganic carbon (DIC), total nitrogen and rapidly available potassium, and significantly reduce the content of dissolved carbon (DC), dissolved organic carbon (DOC) and total dissolved nitrogen (TDN). In addition, the increase of $CO_2$ emission flux was not significant, and gradually decreased with the increase of culture days. The present study provided not only a novel material, but also technology protocol for treatment of acidic wastewater and heavy metals contaminated groundwater and soil.

**Keywords:** Ball-milled tourmaline-biochar; Heavy metal; Adsorption; Groundwater; soil



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# Phosphorus fractions in selected soil types located on the desert and steppe zones of Mongolia

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**ABSTRACT**

The distribution and speciation of soil phosphorus (P) in the solid phase are critical for understanding its biogeochemical transformations and bioavailability to plants. This study investigated P fractions in soils from extensively grazed desert and steppe grasslands in Mongolia, encompassing seven soil types: Calcisols, Cambisols, Solonetz, Phaeozems, Umbrisols, Kastanozems, and Chernozems.

Soil P was fractionated using the sequential Hedley procedure, which separates operationally defined pools including: readily soluble P (extracted with water, $P_{H2O}$), exchangeable/labile P ($P_{EX}$), P bound to Fe and Al oxides ($P_{Fe/Al}$), P associated with Ca ($P_{Ca}$), and residual P (Pres). Plant-available P was additionally assessed using the calcium-acetate-lactate (CAL) extraction method.

Total soil P concentrations varied widely across the studied soils, ranging from 330.4 to 2957.8 mg P $kg^{-1}$. The distribution of P fractions was strongly influenced by soil type and horizon.

Labile and readily available P forms ($P_{H2O}$ + $P_{EX}$, corresponding to the most plant-accessible pools) constituted only a minor proportion of total P, accounting for 0.60% to 7.47%. In contrast, the majority of P was present in recalcitrant forms, predominantly Ca-bound P ($P_{Ca}$) and residual P (Pres), which together comprised 84–99% of total P.

These results indicate that, despite high total P contents in many of the analyzed soils, the proportion of readily plant-available P was generally low. This suggests limited immediate bioavailability of soil P in these arid and semi-arid Mongolian grassland ecosystems, likely due to strong fixation in stable Ca-associated and residual pools, with implications for plant nutrition and ecosystem productivity under extensive grazing management.

**Keywaord**: Mongolian soil phosphorus, bioavailability of soil phosphorus, digestion method of soil phosphorus

# Carbon Cycling in Soils of Northen Coastal Ecosystems

**Pavel Krasilnikov[1*], Ilya Bagdasarov[1], Ann Bobrik[1], Igor Ilichev[1], Georgiy Kazhukalo[2], Stanislav Ogorodov[2], Kristina Prokopyeva[1] and Mihail Tseits[1]**

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**ABSTRACT**

In the context of global climate change in recent decades, extensive data on carbon (C) stocks and dynamics in terrestrial landscapes and in the ocean have been obtained. We know much less about the C cycle in the contact zone of the sea and land – in coastal landscapes. This is due to the complexity of coastal landscapes, where the C source is not only biogenic accumulation, but also the contribution of terrigenous runoff, as well as the input and removal due to the activities of the sea. “Blue carbon” includes the organic carbon (OC) stocks stored by the ocean and the coastal ecosystems (mangroves and marshes) responsible for the long-term OC storage. The main scientific objective of our research was to assess the reserves and dynamics of OC in the biomass and soil organic matter of wetlands on the shores of the seas of the western part of the Arctic Ocean and to model their dynamics under a changing climate.

In soils of marsh ecosystems of the Pomorsky coast of the White Sea C on the most moribund part of the coastal zone was accumulated due to the input of allochthonous, thalassogenic organic matter: the maximum stocks at the lower marsh level are 31.6 $t \cdot ha^{-1}$. At a distance from the boundary of daily flooding, soil C stocks were higher due to biogenic accumulation of organic matter: the maximum value at the upper marsh level is 77.1 $t \cdot ha^{-1}$. Soils of marsh ecosystems of the Pomorsky coast of the White Sea are characterized by low values of $CO_2$ emission (98±16 $mgCO_2 \cdot m^{-2} \cdot h^{-1}$), which indicates their low biological activity. $CO_2$ emission from soils of marsh ecosystems of the southeastern coast of the Barents Sea were high (4.03±0.17 $g\ CO_2 \cdot m^{-2} \cdot day^{-1}$), which indicated their high biological activity. Soils at different levels of marsh ecosystems statistically significantly differ in the value of $CO_2$ emission and are arranged in a series by increasing its values: watts, beaches < littoral baths, eroded marsh ledges < ecotone zones, lower marshes, splash zones of return flow channels (creeks) < middle and upper marshes. The dynamics of the Barents Sea shores were assessed using satellite data. On average for all profiles over the entire study period (1961-2015), the shore dynamics is low (the average rate for all profiles was –0.01 $m \cdot year^{-1}$), but in some periods, significant reformation of different direction was observed along the entire shore.

Climate change, manifested in rising sea levels, increased storm activity and coastal erosion, leads to increased C fluxes from the pedosphere into the hydrosphere and atmosphere. The results of the study contribute to a better understanding of the role in the C balance of coastal ecosystems of the western sector of the Russian Arctic and similar landscapes.

**Acknowledgments**

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# Iron and Manganese Catalyzed Maillard Chemistry: Molecular Characteristics, Evolution Pathways, and Implications for Soil Organic Carbon Formation

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**ABSTRACT**

Mineral-catalyzed Maillard reactions have been proposed as a plausible abiotic pathway for the formation of organic carbon in soil. However, the molecular characteristics of the resulting Maillard products and their linking to real soil organic matter (SOM) remain poorly understood. Here, we conducted abiotic incubation experiments using glucose and glycine as model soil precursors with ferrihydrite (Fh) and birnessite (δ-MnO2) catalysis under environmentally relevant conditions. FT-ICR-MS analysis revealed that both minerals significantly accelerated the polymerization, yielding products that were predominantly categorized as recalcitrant lignin-like compounds, including C15H18O5N2, C16H23O6N3, C18H26O5N2, C19H28O6N2, and C23H33O4N3. Molecular reaction network analysis showed that glucose addition reaction (+ C6H10O5), glycine addition reaction (+ C2H3NO), Strecker degradation (− CO2), and retro-aldol reactions (− C3H6O3 or − C4H8O4) played key roles in molecular evolution. The catalytic mechanisms of Fh and δ-MnO2 were found to be consistent, involving electron acceptance from reducing sugars and cation bridging via dissolved metal ions. Notably, 52.2–84.8% Maillard-like molecules in real soil dissolved organic matter samples, suggesting that the Fh- and δ-MnO2-catalyzed Maillard reactions may represent a significant while previously underappreciated contributor to SOM formation. Together, these findings offer new insights into the mineralogy-mediated pathways that govern the molecular polymerization and persistence of organic carbon in soil systems.

**Acknowledgments**

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# SOM stability and energy storage in soil depending on land use change

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## ABSTRACT

Land use change is a global driver of carbon (C) cycle. The conversion of natural ecosystems to cropland decreases soil C stocks due to removal of plant biomass and increase in soil organic matter (SOM) mineralization because of reduction in C protection caused by tillage. Degraded cropland soils are restored after their abandonment from agricultural use and partially recover organic C stocks. Accumulated organic C serves as a structural and energetic source for soil microorganisms. We used a chronosequence of abandoned croplands (forest steppe zone, MAP: 270-450 mm, MAT: -0.7 °C, soil: loamy Haplic Luvisol) to examine effects of natural restoration on SOM stability and energy storage in soil. We used thermal approach (thermogravimetry and differential scanning calorimetry) combined with 180-day soils incubation and SOM density fractionation.

The soils sequestered 0.85 Mg C $ha^{-1}$ $y^{-1}$ (0-30 cm) during 25 years after cropland abandonment. In abandoned soils, thermally labile SOM with an activation energy of 69 kJ·$mol^{-1}$ accumulated 2.8 times faster than did stable SOM with a higher energy barrier to combustion (80 kJ·$mol^{-1}$). Microorganisms use mainly thermally labile SOM, whose content decreased by 10–24% over 180 days of soil incubation. The increase in energy availability and microbial activity in restored soils led to faster C and nutrient cycling in the abandoned cropland than in current agricultural lands. Mineral-associated organic matter stored 1.7 times more energy per unit of C (42 kJ·$g^{-1}$C) than did the free and occluded particulate organic matter (25 kJ·$g^{-1}$C). Free particulate organic matter was the dominant energy pool in the restored soil and increased microbial activity. Restored and natural soils had a lower thermal stability of SOM and greater microbial decomposability than the cropland soils.

Due to the preferential accumulation of C with lower thermal stability and with greater susceptibility to microbial decomposition in the restored soils, greater $CO_2$ release could occur if these lands are retiled – will be involved again in agricultural use. The content of thermally stable C also increased in abandoned soils; therefore, we should account for the ecological balance between C sequestration and release after the natural restoration of croplands.

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# Dual-Domain Regulation of Dissolved Organic Matter Release in Soil: The Role of pH and Calcium

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**ABSTRACT**

Dissolved organic matter (DOM), being the most reactive soil organic matter (SOM) fraction, affects key biogeochemical processes in soil like nutrient cycling, pollutant transport, and organic carbon sequestration. Quantitative understanding of physical-chemical processes regulating the release of DOM in response to variation in factors such as pH and Ca concentration is still lacking. Here, we conducted batch experiments and employed the NOM-CD (Natural Organic Matter-Charge Distribution) model and the NICA-Donnan (Non-Ideal Consistent Competitive Adsorption-Donnan) model to investigate the physical-chemical processes controlling DOM release in seven agricultural topsoils under varying pH (3-9) and Ca concentration (0-10 mM). The DOM fractionation results showed that while hydrophilic acid (Hy), fulvic acid (FA), and humic acid (HA) concentrations increased with pH, their contribution to total DOM differed: Hy and HA dominated at respectively low pH (~4-6) and high pH (~8-9), whereas FA peaked at near-neutral pH (~6.5-7). Our NOM-CD model calculations revealed that changes in the DOM concentration at low pH (pH<~5-6.5) were mainly due to OM desorption from soil minerals. Changes in the DOM concentration at high pH (pH>~5-6.5) were predominantly controlled by OM dissolution, as demonstrated by the relation between the DOM concentration and Donnan potential ($\varphi_D$) of DOM calculated with the NICA-Donnan model. Based on these findings, we propose a conceptual Dual-Domain Desorption Dissolution model in which the relative importance of these two controlling mechanisms is quantitatively assessed for the first time. These insights will be helpful to better quantify soil management effects on the stability and functioning of SOM.

# Abiotic Methane Production Driven by Soil Reactive Oxygen Species

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**ABSTRACT**

Methane ($CH_4$) emissions from wetlands are traditionally attributed to microbial methanogenesis under anoxic conditions. However, recent studies have suggested that non-enzymatic, reactive oxygen species (ROS)-driven processes may also produce $CH_4$ in biological systems. Here, we extend this concept to soil environments and demonstrate that ROS can drive substantial abiotic $CH_4$ formation during redox fluctuations in wetland soils. Through controlled incubations of soils collected from 14 wetlands across China, we show that fluctuating redox conditions promote ROS generation, which in turn oxidizes soil organic matter and yields $CH_4$ abiotically.

These findings reveal that abiotic $CH_4$ formation is not a rare or laboratory-specific phenomenon but a widespread and dynamic process within natural wetland ecosystems. By coupling the redox cycling of iron, organic matter, and ROS, this mechanism operates independently of microbial methanogenesis yet contributes measurably to total $CH_4$ fluxes. Our results challenge the long-held assumption that wetland $CH_4$ emissions are solely biological in origin and call for a reassessment of methane budgets that overlook abiotic sources. Furthermore, we show that hydrological management strategies including alternate wetting and drying (AWD), commonly implemented to mitigate $CH_4$ emissions, may unintentionally enhance ROS-driven abiotic $CH_4$ production. Recognizing and quantifying this process provides a new framework for understanding methane cycling under fluctuating redox conditions and offers critical insights for greenhouse gas mitigation in wetland and agricultural systems.

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# Controlling factors on soil organic matter stability under threat of global warming and drought in central Asian semi-arid mountain ecosystems

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**ABSTRACT**

The Altai and Tianshan Mountains of eastern Kazakhstan represent two major ecological and climatic barriers in Central Asia and are warming substantially faster (0.27–0.45 °C decade$^{-1}$) than most temperate regions (0.15–0.25 °C decade$^{-1}$; IPCC, 2023). Such accelerated warming and increasing drought are expected to alter soil organic matter (SOM) dynamics, yet the controlling factors of SOM stability in this mountain ecosystems remain poorly resolved. In this study, 48 soil samples were collected in the Altai and Tianshan Mountains, ranging from around 500 m to 3000 m in elevation. Rock-Eval® thermal analysis was used to quantify long-term SOM stability ($PARTY_{SOC}$ stable OC content) and chemical stability (R-index). Pyrolysis-GC/MS was used to investigate SOM molecular composition of the soils. Links among SOM molecular composition, climatic parameters and other soil properties were investigated using principal component analysis, multiple regression analysis, and correlation analysis. We found that climatic and mineralogical factors jointly structured SOM molecular composition, which was highly sensitive to vegetation, exchangeable Ca/Mg, Al/Fe oxides, elevation, MAT and aridity. The first composition axis (PC1) contrasted plant-derived structural biopolymers with condensed aromatic–N-rich material: scores were high in samples enriched in lignin-derived compounds, long-chain lipids and terpenoids, and low where bulk aromatics and N-heterocyclic compounds dominated. The second axis (PC2) primarily captured a gradient from carbohydrate- and short-chain lipid-rich SOM (high scores) towards N-containing and aromatic-enriched fractions (low scores). Chemical stability ($R^2$ = 0.84) was overwhelmingly governed by molecular composition, with a strong negative effect of PC1 (Std.Est = −0.85), and was further modulated by aridity. This indicates that chemically resistant SOM fractions in this region are tightly coupled with both molecular architecture and drought stress. In contrast, long-term SOM stability was governed predominantly by exchangeable Ca/Mg and Al/Fe oxides, with only secondary contributions from SOM composition, indicating stabilization via associations of SOM with exchangeable Ca/Mg and Al/Fe oxides. These results suggest that ongoing climate change is likely to have a strong impact on the chemically resistant SOM pool, whereas the long-term stable SOM pool may be comparatively buffered on decadal timescales under climate change.

**Acknowledgments**

Rock-Eval® is a trademark registered by IFP Energies Nouvelles.

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# Do cover crops and no-tillage reshape soil biota and organic matter across depth?

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**ABSTRACT**

Addressing the challenge of improving soil health and carbon sequestration through sustainable agricultural practices requires a deeper understanding of how management strategies shape soil biota and organic matter (OM) dynamics across the entire soil profile. Soil biota is a key driver of nutrient cycling and carbon stabilization, yet processes occurring in the subsoil remain poorly understood. Our study aimed to investigate how different farming systems affect the structure of bacterial, fungal and invertebrate communities from 0–60 cm depth, and how any shifts relate to OM distribution, quality and stocks.

A 10-year wheat-maize rotation trial on a Calcaric Eutric Cambisol in central Italy was assessed, by comparing: i) integrated management without cover crops and conventional tillage (CONV); ii) organic management with grass-legume cover crops, temporary wheat-faba bean intercropping and conventional tillage (ORG); and iii) integrated management with grass-legume cover crops and no-tillage (NOT). Soils were sampled by genetic horizons. Microbial and metazoan communities were assessed via DNA metabarcoding (16S, ITS, COI), and OM was fractionated into labile, stable and resistant pools. Bulk soil and fractions were analyzed for organic carbon and total nitrogen, and their stocks were estimated. Further, available phosphorous was measured in bulk soil, and the chemical composition of mineral-associated OM (MAOM) was studied by $^{13}C$ NMR.

Significantly ($p < 0.05$) higher bacterial and fungal richness was observed in NOT topsoil and subsoil, respectively. diversity clearly separated NOT from ORG and CONV, also indicating enhanced depth-dependent differentiation under no-tillage. ORG and CONV showed no significant differences in and diversity, although the relative abundances of few taxa differed, e.g. ORG was enriched in rhizobia (genera *Mesorhizobium* and *Bradyrhizobium*), even at greater depths than NOT.

OM patterns reflected similar biota differences. NOT promoted OM stratification due to no-tillage, with higher content in topsoil and greater abundance of labile forms, also in MAOM. ORG and CONV had more homogenized OM distribution along the soil depth, dominated by stable and more decomposed pool. However, ORG and NOT recorded higher proportion of sand-size aggregates and associated OM, suggesting improved structural development driven by cover crops. Total OC stocks (0–60 cm) did not differ significantly among systems.

In conclusion, reduced disturbance and continuous organic inputs reshape soil biota and OM dynamics across depth, altering community structure and carbon stabilization pathways.

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# National mapping of cropland soil pH buffer capacity and acidity debt in China

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**ABSTRACT**

Thomas (1996) claimed that "Soil pH is probably the single most informative measurement that can be made to determine soil characteristics". Soil pH buffering capacity (pHBC) determines the resilience of soils to acidification, yet its national-scale distribution across China's croplands remains poorly quantified. In this study, 22 representative soil samples covering major agroecological zones were analyzed to develop pHBC prediction models based on key physicochemical properties, including carbonate content, cation exchange capacity (CEC), and particle-size distribution. Multiple linear regression (MLR), ridge regression (RR), and least absolute shrinkage and selection operator (LASSO) models were compared, with MLR demonstrating superior predictive performance and interpretability ($R^2$=0.95 for alkaline–neutral soils and 0.77 for acidic soils). Using the optimal MLR models and national soil datasets, the first spatially explicit map of cropland pHBC across China was generated using 1083 national soil physicochemical grid data published by (FAO&IIASA, 2023), revealing a pronounced north–south gradients (**Fig.1**, <8 to >800 mmol $kg^{-1}$ $pH^{-1}$). High pHBC zones occur primarily in calcareous soils of northern and northwestern China, whereas low pHBC values dominate in the highly weathered acidic soils of the south. Building upon this, a novel index, soil acidity debt, was proposed to quantify the total proton load a soil can absorb before reaching the critical pH threshold of 5.5. The resulting map shows that 49.3% of China's cropland remains acid-safe, 35.3% is at potential risk, and 15.4% has exceeded its buffering limit. Spatial divergence in acidity debt reflects the combined effects of carbonate buffering, climatic leaching, and anthropogenic nitrogen inputs. The integrated pHBC–acidity debt framework provides a quantitative foundation for precision liming, sustainable fertilizer management, and region-specific soil remediation, offering new insight into soil acidification dynamics and a scientific basis for national soil conservation policy.

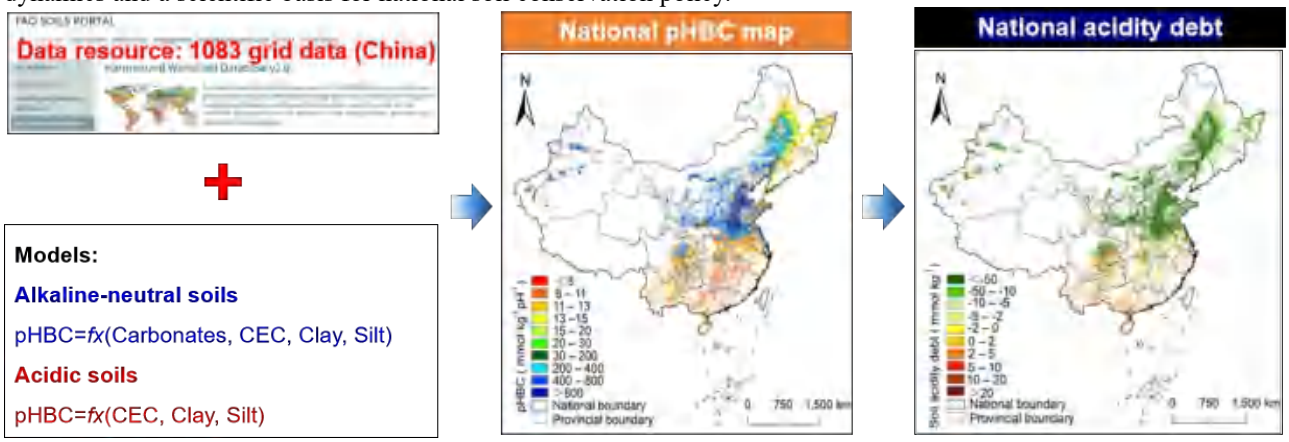



**Fig. 1** Generation process of the national mapping of cropland soil pHBC and acidity debt in China

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# Impact of active Al and Fe on mineral-associated organic matter in acidic to alkaline tropical to subtropical non-volcanic soils

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**ABSTRACT**

Understanding controls on soil organic carbon (SOC) stabilization is essential for predicting its distribution and sequestration potential. Controls on mineral-associated organic carbon (MAOC), the dominant long-term SOC pool, remain poorly understood across pH gradients, particularly in tropical and subtropical regions. Here, we analyzed topsoils from 66 non-volcanic sites under mainly natural vegetation in India, Tanzania, Cameroon, Japan, and Indonesia, spanning broad gradients in SOC (1.2–50.7 g $kg^{-1}$), moisture (EP, effective precipitation, −1740 to 2850 mm), and corresponding pH (3.9–9.2). Soils were grouped as strongly acidic (pH ≤ 5.5), weakly acidic (5.5 < pH ≤ 7), and alkaline (pH > 7). We quantified MAOC (> 1.7 g $cm^{-3}$ and < 53 µm), microbial necromass, and key predictors including active Al/Fe (oxalate-extractable Al + Fe), clay content, and exchangeable Ca + Mg. Structural equation models (SEMs) quantified the contributions of MAOC-related factors. C-stabilization capacity of active Al/Fe (mol C per mol active Al/Fe) was derived from unstandardized SEM coefficients.

MAOC comprised 77 ± 15% of SOC across sites, with acidic soils showing higher SOC, MAOC, and active Al/Fe. Correlation and SEMs identified active Al/Fe, rather than clay content, as the primary positive regulator of MAOC. pH-stratified SEMs showed active Al/Fe content explained most of the variation in MAOC across all pH classes ($\beta > 0.47$, $R^2 > 0.78$ in all, strongly acidic, and weakly acidic soils; $\beta = 0.59$, $R^2 = 0.53$ in alkaline soils). Exchangeable Ca + Mg did not significantly influence MAOC, even in alkaline soils, indicating that Ca and Mg play a minor role in MAOC stabilization at this scale. The C-stabilization capacity of active Al/Fe was similar in strongly and weakly acidic soils (5.6 mol C per mol active Al/Fe) but lower in alkaline soils (3.7 mol C per mol active Al/Fe), likely due to reduced positive surface charge and fewer reactive hydroxyls. Necromass C was substantially higher in acidic than alkaline soils, and its proportion in MAOC (64 ± 22%) and positive correlation with active Al/Fe occurred only in acidic soils. This indicates that MAOC formation in acidic soils is closely tied to Al/Fe-mediated stabilization of microbial necromass via charge-driven sorption and ligand exchange. The non-necromass component of MAOC also increased with active Al/Fe but showed little pH dependence, suggesting robust inner-sphere complexation or Al/Fe-mediated aggregation. Together, active Al/Fe controls MAOC across tropical and subtropical soils, but its C-stabilization efficiency is pH dependent because microbial necromass is preferentially stabilized in acidic soils, leading to a lower MAOC in alkaline soils. Thus, both active Al/Fe abundance and pH (influenced by effective precipitation) must be considered when predicting MAOC stocks, composition, and SOC sequestration potential.

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# Insight in the characteristics of humic substances with crop straw derived organic materials amendments

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**ABSTRACT**

Carbon sequestration by application of organic materials and biochar in soil is an important strategy to increase soil organic carbon (SOC), but the stability of SOC, particularly humic substances (HS) vary with the types of organic material. In this study, cotton straw and its derived compost and biochar were added with equivalent carbon content to soil and incubated for 180 days. The structural characteristics of humic acid (HA), fulvic acid (FA) and humin (Hu) were investigated using solid-state $^{13}C$ nuclear magnetic resonance (NMR) and Fourier transform infrared (FTIR) spectroscopy. The results showed that biochar treatment increased the aryl C of HA, FA, and Hu by 1.38%, 1.68%, and 10.46% compared to straw treatment and increased the aryl C of HA, FA, and Hu by 1.46%, 1.99% and 2.01% compared to compost treatment. The O-alkyl C of HA was 10.59% and 10.65% in high biochar/straw and biochar/compost ratios respectively, while it was 9.81% and 9.61% in low biochar/straw and biochar/compost ratios. In addition, the O-alkyl C of FA was 62.83% and 58.48% in high ratios of biochar/straw and biochar/compost, respectively, while it was 55.85% and 55.94% in low ratios of biochar/straw and biochar/compost. These results suggest that biochar is advantageous for aryl C formation of FA and Hu due to its high aryl C content, whereas straw or compost is advantageous for alkyl C formation of HA. The stability of aryl C and O-alkyl C of HA, FA, and Hu can be improved in soils by incorporating biochar in combination with straw or compost.

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# Abiotic Processes Dominate Short-Term Carbon Emissions in Sandy Soil after Soil Rewetting: Impact of Mineral and Reactive Oxygen Species

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**ABSTRACT**

Microbial respiration is the conventional paradigm for explaining short-term pulsed releases of $CO_2$ during soil drying–rewetting (D/RW) cycles. However, a rapid pulse onset and lagging microbial recovery have been measured in soils that experienced severe drought after D/RW, raising the question of whether abiotic carbon mineralization is also a prevalent phenomenon, particularly in sandy soils with prolonged aridity. Through soil incubation experiments, including microbial growth monitoring and sterilization, we identified the crucial role of abiotic processes in soil organic carbon (SOC) mineralization during D/RW. In sandy soil, abiotic processes accounted for 95.5% of total $CO_2$ emissions within three hours of rewetting, compared to only 39.5% in paddy soil. Concurrently, the solid-liquid reaction in D/RW process mediated the redox cycle of Fe, Mn, and reactive oxygen species (ROS) production, directly promoting SOC mineralization. Further, ROS participated in SOC degradation through synergistic effects with enzyme activity. These abiotic processes mainly resulted in removing molecules with low H/C ratios (<1.24) and high unsaturation in DOM, which are more difficult for microbes to degrade. Our findings highlight the importance of abiotic reactions in short-term SOC mineralization after D/RW process, offering a novel framework for evaluating carbon emissions in sandy soils of arid and semi-arid regions.

**Acknowledgments**

This work was completed under the supervision of Professor Hanzhong Jia and Associate Professor Kecheng Zhu at Northwest A&F University. The authors gratefully acknowledge their strong guidance and invaluable support throughout this research.

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# Carbon sequestration dynamics of MAOC in the tea plantation with different ages: evidence from Fe/Al oxides and organo–mineral interactions

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**ABSTRACT**

Mineral-associated organic carbon (MAOC) is critical for long-term soil carbon sequestration, yet its accumulation dynamics and constraints in acidic agroecosystems remain unclear. Using a chronosequence (6, 20, 29 years) of tea plantations, we investigated the dynamics of MAOC and its mineralogical characteristics in topsoil (0-20 cm) and subsoil (20-40 cm). We found that while MAOC stocks increased with plantation age, its accumulation rate significantly declined, especially in subsoils. Sequential extraction revealed that organically complexed Fe/Al ($Fe/Al_{PP}$) was the dominant form of mineral-associated carbon. However, the formation of $Fe/Al_{PP}$ was suppressed over time, directly limiting further MAOC increase. Mineralogical and spectroscopic analyses showed that prolonged tea cultivation promoted the transformation of reactive, high-surface-area Fe phases (e.g., ferrihydrite) to more crystalline, low-surface-area goethite, reducing the reactive mineral surface area available for carbon binding. Concurrently, the chemical nature of MAOC shifted from plant-derived alkyl-C to microbial-derived, oxygen-rich carboxylic/amide-C. These bulky, hydrophilic molecules create a "crowding effect," sterically hindering the formation of stable inner-sphere complexes on remaining mineral surfaces. We conclude that the deceleration of MAOC accumulation in acidic tea soils is co-limited by the depletion of reactive Fe/Al phases and the progressive occupation of mineral surfaces by less-stabilizable, microbial-processed organic matter. This dual mechanistic constraint defines the finite saturation capacity of MAOC in these important carbon-sink ecosystems.

**Acknowledgments**

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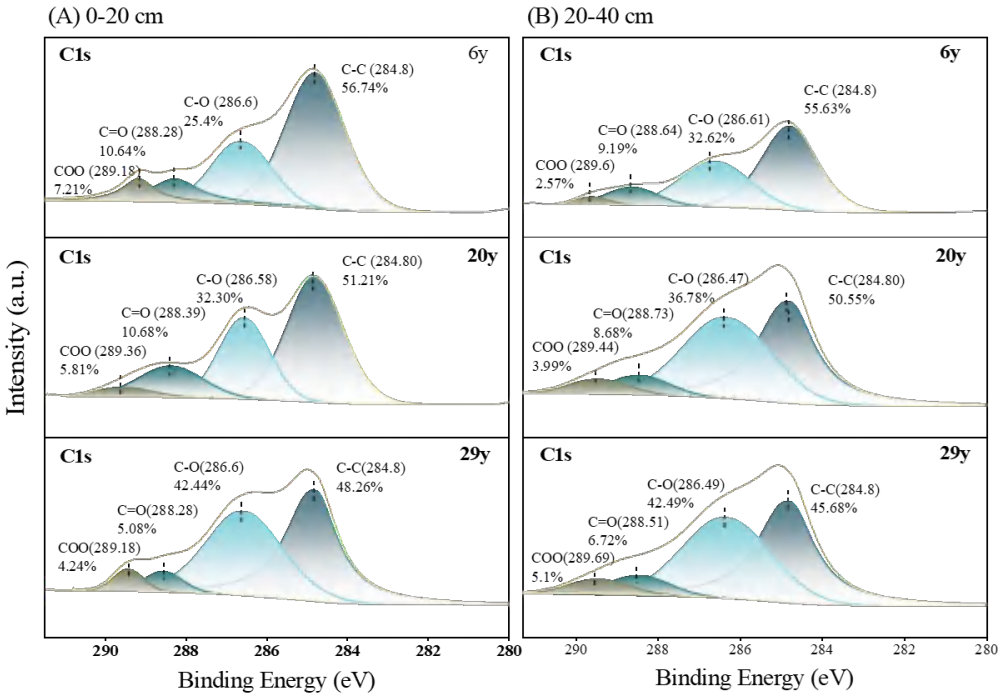



Fig.1 XPS spectra of C1s of MAOC in the tea plantations with different ages.

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# Establishing trees into permanently grazed grassland to increase SOC stocks – scaling results from microbes to landscapes

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**ABSTRACT**

New Zealand has moderate to high levels of soil organic carbon (SOC) in part due to the temperate climate, soil mineralogy and dominance of permanently grazed grassland land use. To offset greenhouse gas emissions and meet New Zealand's net zero target, a focus has been on establishing new extensive permanent forests to act as a carbon sink. We hypothesised that a targeted integration of smaller groupings of trees within grassland soils could achieve significantly greater carbon stocks, per unit land area due to the presence of edge effects, whereby increases in SOC stocks could also occur.

Here we will present findings and insights from a large national scale research programme investigating whether the integration of small grouping of trees within grazed grasslands can increase SOC stocks. We quantified and examined the relationship between SOC stock, soil fractions (POC and MAOC) and microbial abundance along grassland to forest gradients.

Our evidence suggests that integration of trees into grassland soils can increase SOC stocks in certain soil types, particularly those with a lower capacity to store carbon (e.g. soils with a low surface area). We also measured a change in microbial composition along these grassland to forest gradients with metagenomics data underway to understand whether this change in composition caused a change in microbial function.

Furthermore, data from this research programme is being used to validate and parameterize a microbially-informed model to allow predictions of changes in soil carbon stocks associated with the establishment of trees within grassland soils. The outcome of these model scenarios will be incorporated into geospatial models to project SOC scenarios at the landscape to national scale.

# Non-linear regulation of soil organic carbon by salinization: aggregate–microbe coupling

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**ABSTRACT**

Soil salinization and alkalization are key environmental factors limiting agricultural productivity and soil carbon sequestration. Labile and recalcitrant carbon pools play distinct roles in maintaining carbon balance, yet their responses to different types and degrees of salinization remain unclear. Here, we investigated three typical saline–alkaline soils (saline, sodic, and secondary salinized) in the Ningxia Irrigation District, analyzing soil physicochemical properties, aggregate structure, carbon fractions, enzyme activity, and microbial communities across four salinization levels (non-, light, moderate, and high). Results showed that across the salinization gradient, macroaggregates became fragmented, microaggregates were enriched, and soil structural stability declined significantly (decreased MWD and GMD, increased D and PAD), thereby weakening the physical protection of organic carbon. Labile carbon pools (POC, DOC, MBC) exhibited a >60% reduction , whereas recalcitrant carbon (MAOC) remained relatively stable. Enzyme activities and microbial diversity declined significantly, with community composition shifting toward halotolerant and oligotrophic taxa. Region-specific patterns were observed: the three soil types (saline, sodic, and secondary salinized) exhibited labile carbon loss and relative preservation of recalcitrant carbon, but the dominant mechanisms differed. In saline (HN) and sodic (XDT) soils, carbon dynamics were primarily governed by salinity stress and aggregate degradation, while in secondary salinized soils (HSB), the coupling of aggregates and microbial function enhanced the transformation of carbon into mineral-associated forms, supporting a relatively stable recalcitrant carbon pool. This study reveals the multi-pathway regulation of soil organic carbon under salinization, highlighting the non-linear response of carbon stability to soil type and formation process, and provides theoretical guidance for ecological restoration and carbon sequestration management in saline–alkaline soils.

**Keywords:** Saline–alkaline soils, Soil aggregates, Microbial community, Labile carbon, Recalcitrant carbon, Carbon stability

# Interactive effects of straw and biochar reorganize humic acid molecular architecture toward coupled reactivity and persistence

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## ABSTRACT

Humic acid (HA), a key component of soil humic substances, plays a crucial role in soil fertility and ecological functioning. To elucidate the structural heterogeneity of HA under the interactive effects of straw and biochar, we conducted a systematic incubation experiment with single and combined applications of straw and biochar. Multiple complementary techniques (including elemental analysis, electron paramagnetic resonance (EPR), fluorescence spectroscopy, solid-state $^{13}C$ nuclear magnetic resonance (NMR), and Fourier transform ion cyclotron resonance mass spectrometry (FTICR-MS)) were employed to characterize HA at the molecular level. Organic amendments significantly increased the oxygen content, polarity, and hydrophilicity of HA molecules, while also enhancing free-radical concentrations and molecular-level structural complexity. Biochar addition primarily promoted aromaticity and supramolecular condensation, whereas straw inputs enriched oxygenated moieties and increased molecular biodegradability. Strikingly, their combined application enhanced radical concentration and chemical activity while generating less condensed aromatic structures, resulting in HA molecular assemblages that combine features commonly associated with higher chemical reactivity and increased structural persistence.

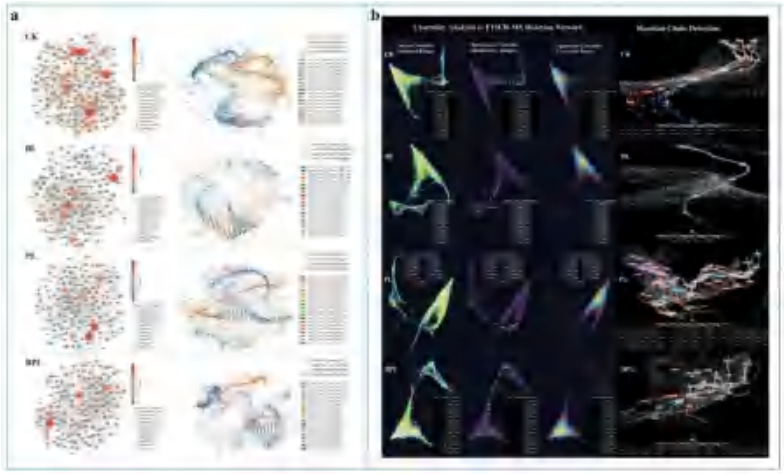


Figure 1. Network organization and modular structure of humic acid (HA) molecular assemblages under different treatments (a), and centrality landscape(left) and reaction backbone chain detection(right) of HA molecular reaction networks under different treatments (b).

Together, these results support a conceptual framework linking reactivity and stability, in which labile and recalcitrant organic inputs are associated with distinct yet integrated patterns of HA molecular organization. Beyond site-specific implications, this study provides new strategies and theoretical foundations for optimizing soil organic matter stability and fertility, offering guidance for sustainable agricultural management and carbon sequestration.

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# Functional Cover Crop Diversity Enhances Root-Driven Organo-Mineral Associations and Nutrient Efficiency in High-Latitude Agriculture.

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**ABSTRACT**

In high-latitude arable systems (63.9°N), short growing seasons and cold climates often constrain regenerative practices. This study investigates how cover crop (CC) diversity influences the synergy among root development, carbon (C) persistence, and nutrient (N and P) dynamics within a Nordic barley (*Hordeum vulgare L.*)-oat (*Avena sativa*) rotation. Over three years, we evaluated a gradient of CC intercropping complexity using a randomized complete block design. Treatments were: (1) Control (barley without NPK), (2) Biochar-Fertilizer (barley + NPK + 1.8 Mg $ha^{-1}$ $year^{-1}$ biochar), (3) Monocrop (barley), (4) Ryegrass (barley + ryegrass), (5) Clover (barley + ryegrass + white/red clover), and (6) Chicory (barley + ryegrass + red clover + chicory + bird's-foot trefoil). We quantified root biomass, soil organic matter (SOM) fractions , specifically Mineral-Associated Organic Matter (MAOM) and Particulate Organic Matter (POM), aggregate stability, nutrient stocks, and microbial abundance via qPCR.

The CCs were successfully established, with an average biomass of 1525 kg/ha, without compromising cereal yields, thereby confirming their viability in Nordic climates. A central finding was that root development served as the primary driver of organo-mineral associations. Ryegrass- and Clover-based systems produced significantly higher root biomass, which correlated strongly ($p < 0.01$) with MAOM stocks and total P acquisition. These systems stored 12 Mg/ha more MAOM-C and 1.1 Mg/ha more MAOM-N than the control at 0-20 cm depth.

The inclusion of diverse functional traits in the complex five-species mixture significantly improved soil physical structure, yielding higher aggregate stability and lower bulk density. While CCs accumulated approximately 7 kg P/ha, the diverse mix optimized nutrient availability, whereas simpler mixtures showed higher C:P ratios, suggesting potential microbial P immobilization. Microbial abundance was consistently higher in multi-species treatments, indicating a more active biological environment.

Ongoing analysis integrates cereal physiological data, focusing on the photosynthetic efficiency of oats in response to these altered nutrient regimes. These findings bridge the gap between root architecture, plant physiology, and long-term SOM persistence, providing a strategic framework for using functional crop traits to enhance soil resilience and nutrient efficiency in cold-climate regions.

**Acknowledgments**

This work has been supported by NordForsk through the AgroMixNorth Project and by the Norwegian Directorate of Agriculture through the JorNor Project.

# Molecular–thermal coupling of plant residue-derived organic matter mediated by clay minerals: insights from solid-state 13C NMR

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**ABSTRACT**

Clay minerals strongly influence the persistence of soil organic matter (SOM), yet the links between mineral-specific molecular transformations and organic matter (OM) stability remain insufficiently quantified. We incubated *Artemisia princeps* residues for 360 days in quartz-, kaolinite-, and montmorillonite-based artificial soils and characterized plant-derived OM associated with these minerals using solid-state $^{13}C$ CP/MAS NMR and thermogravimetry–differential thermal analysis (TG–DTA). In quartz soil, $^{13}C$ NMR spectra showed a shift from O-alkyl-dominated, polysaccharide-rich material to residues enriched in alkyl- and carbonyl-C, with smaller changes in aromatic-C, providing an unprotected decomposition baseline. Kaolinite-associated OM retained relatively high O-alkyl-C and showed only moderate increases in alkyl- and carbonyl-C, resulting in low alkyl/O-alkyl ratios and more plant-like signatures, indicating that kaolinite slows both decomposition and structural transformation. By comparison, montmorillonite-associated OM had the lowest O-alkyl-C, the highest alkyl- and carbonyl-C, slightly elevated aromatic-C, and alkyl/O-alkyl > 1, indicating selective accumulation of highly processed, alkyl- and carboxyl-rich residues on 2: 1 clay. These mineral-specific NMR patterns suggest distinct clay controls: kaolinite dampens the progression from plant-like to microbially transformed OM, whereas montmorillonite sustains a sorption-constrained, low-flux OM – microbe – clay microenvironment in which strong mineral protection suppresses net $CO_2$ production and microbial metabolism, yet gradual compositional shifts can accumulate during slow turnover of mineral-associated OM. TG–DTA further showed higher decomposition temperatures and larger residual mass for clay-associated OM than for quartz. By integrating NMR and thermal data into simple indices of estimated mean residence time (*eMRT*) and activation-energy equivalent (*Ea-equivalent*), we quantified how these energetic parameters covary with alkyl/O-alkyl ratio and related molecular features. Overall, different clay minerals impose contrasting C-stabilization regimes that co-shape OM molecular composition and energetic resistance, highlighting mineral-specific molecular–thermal coupling as a key control on the stabilization of plant residue-derived SOM in clay-rich soils.

**Keywords:** Clay mineralogy; Organo–mineral stabilization; Thermal stability; Activation energy

**Acknowledgments**

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# Soil organic carbon sequestration potential and stability in Solonetzic and Vertisolic soils of the North American Prairie

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**ABSTRACT**

Retaining soil organic carbon (SOC) and understanding its stability/persistence are essential for achieving long-term carbon sequestration goals, maintaining soil fertility, and promoting soil health. Soils vary in their potential for carbon sequestration. Understanding the biophysical limits of different soils helps identify regional, soil-specific management strategies and determine the maximum storage capacity of SOC, especially in organo-mineral associations constrained by reactive minerals. These processes range from global factors, such as climate, to complex soil biogeochemical interactions at organo-mineral surfaces. Therefore, improving our understanding of the dynamics that contribute to SOC persistence—from the microscale to the soil profile and landscape level—as well as the mechanisms that protect it, enhances our ability to predict changes in the soil carbon reservoir amid global environmental shifts. Organo-mineral interactions have been regarded as the primary mechanism for stabilizing SOC over decades to millennia. Although substantial progress has been made in understanding carbon persistence and turnover, the fundamental mechanisms that underlie pedogenic soil properties remain underinvestigated. This research analyzes SOC to evaluate stability, persistence, and carbon sequestration potential, based on soil properties at the molecular and microstructural levels, in Solonetzic and Vertisolic soils from southern Saskatchewan in the Canadian portion of the North American Prairie. In the Fall of 2025, three intact soil core samples—3 inches in diameter and 24 inches deep from the surface—were collected from both Vertisolic and Solonetzic soils, classified in the field under the Canadian Soil Classification System. Three replicates per location were obtained using a punch truck. The study employs synchrotron-based X-ray Computed Tomography (CT) to obtain three-dimensional microstructural data, enabling visualization and analysis of pore size, connectivity, distribution, and volume, as well as the spatial arrangement of SOC fractions relative to soil features and pore spaces. X-ray fluorescence imaging (XRF) will map carbon content and composition, providing a detailed view of the distribution of total SOC and identifying carbon-rich zones. Near-edge X-ray absorption fine structure (NEXAFS) spectromicroscopy will produce spatially resolved data on SOC species by analyzing intact samples containing root fragments, SOC, and soil pores. Fitting the obtained data to References spectra will identify spatial patterns of aromatic, aliphatic, and carboxylic carbon compounds associated with different features. This research provides critical visual insights into how pore structures affect the distribution of organic molecules; hence, understanding the molecular details of SOC in specific pedogenic soil types can inform soil management practices aimed at carbon sequestration by leveraging the soil's inherent capacity.

**Keywords:** Soil organic carbon; Synchrotron-based spectroscopy and imaging; Soil organic carbon persistence; Carbon sequestration; Soil order.

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# Soil Organic Carbon Dynamics During Vegetation Restoration Across Dryland Precipitation Gradients Revealed by Radiocarbon Isotopes and Microbiology

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**ABSTRACT**

The interaction between soil organic carbon (SOC) dynamics and microbial activity is crucial for understanding the mechanisms that govern carbon storage and turnover in terrestrial ecosystems. Changes in precipitation patterns can significantly affect SOC distribution and cycling processes by altering vegetation structure, which, in turn, influences regional ecosystem carbon balances. However, the systematic understanding of SOC turnover, particularly in deep soil layers, and its microbial driven mechanisms across varying precipitation gradients during afforestation remains limited. To address this, our study examines afforestation chronosequences across three distinct precipitation gradients: semi-arid, arid, and hyper-arid regions. At each gradient, soil samples were collected from depths of 0-500 cm from plots representing five vegetation restoration years, with non-afforested land employed as the control. Using a combination of physical SOC fractionation and radiocarbon dating techniques, we characterized the dynamics and turnover times of deep SOC and its fractions over the vegetation restoration process. Furthermore, molecular ecological approaches were used to analyze shifts in microbial community composition, abundance, and functional groups involved in carbon cycling, with particular emphasis on identifying key carbon-sequestering microbial phylum, carbon cycling genes and their associations with specific SOC fractions. This research aims to elucidate the microbial mechanisms responsible for the accumulation and stabilization of deep SOC during vegetation restoration. By integrating data across precipitation gradients, vegetation restoration years, microbial communities, and SOC turnover, we aim to clarify the interactions among these factors. Our findings are expected to advance the understanding of climate and ecosystem carbon cycle feedbacks and offer empirical guidance for enhancing vegetation restoration and carbon management strategies in dryland regions.

**Key words**: dryland region; vegetation restoration years; deeper soil; soil organic carbon; soil microbes

**Acknowledgments**

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# Changes in Deep-Profile Soil Organic Carbon and Influencing Factors During Planted Vegetation Restoration in Alpine Regions

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## ABSTRACT

Vegetation restoration is a critical strategy for rehabilitating ecosystems in alpine arid regions, influencing the vertical distribution of soil organic carbon by regulating microbial community structure. However, the microbial mechanisms underlying this process remain poorly understood. Therefore, this study investigates the microbial effects of vegetation restoration on soil organic carbon within the 0–500 cm soil profile, comparing planted *Caragana microphylla* shrub forest and mobile dunes (CK) at different restoration ages (5, 10, 15, 23, and 36 years) in the Gonghe Basin, China. The study area is situated at an elevation of 2,871 to 3,870 meters above sea level, with an annual mean temperature of 3.9°C and average annual precipitation of 246.3 mm, primarily occurring between May and September. The annual mean potential evaporation is 1,716.7 mm, resulting in an exceptionally arid climate. This region is classified as an alpine arid zone, with predominantly sandy soils. Results indicate that the mean soil organic carbon content within the 0–500 cm soil profile was 1.18 $g \cdot kg^{-1}$, with reserves ranging from 55.82 to 144.99 $t \cdot hm^{-2}$. Microbial biomass carbon averaged 4.11 $mg \cdot kg^{-1}$. With increasing vegetation restoration duration, soil organic carbon content and reserves in the 0–500 cm profile exhibited distinct trends at 5, 10, and 15 years, showing significant increases at 23 and 36 years of restoration. At 23 years, soil organic carbon content and reserves in the 0–500 cm profile were 1.5 and 1.8 times those of the control (CK), respectively, while at 36 years, these values were 1.8 and 2.2 times those of CK. Vertically, soil organic carbon content initially decreased, followed by an increase across all restoration periods. Moisture emerged as a key environmental factor regulating deep soil organic carbon sequestration in alpine arid regions. Microbial biomass carbon exhibited a significant positive correlation with soil organic carbon content. Microbial α-diversity within the 0–500 cm soil profile increased markedly with restoration duration, while microbial gene abundance associated with carbon sequestration functions significantly increased during the later restoration phases. In summary, vegetation restoration drives changes in microbial community structure and carbon sequestration capacity by altering soil structure, thereby promoting deep soil organic carbon accumulation. This study elucidates the microbial mechanisms underlying soil carbon sink formation during vegetation restoration in alpine arid regions from the perspectives of microbial diversity and carbon sequestration genes, offering significant implications for ecological restoration and carbon management in degraded alpine desert areas.

**Key Words:** alpine arid regions; vegetation restoration; soil organic carbon; soil microbial diversity; carbon cycle functional genes

**Acknowledgments**

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# Typical mineral additions promote soil mineral-associated organic carbon sequestration: Interactions between Fe oxides and microbial-derived peptides

**Qi Li[1], Hengjie Liu[2], Linfeng Li[1], Anwen Xiao[1], Weifang Hu[1], Fenghua Zhai[1], Bohao Yin[3], and Yichun Li[1*]**

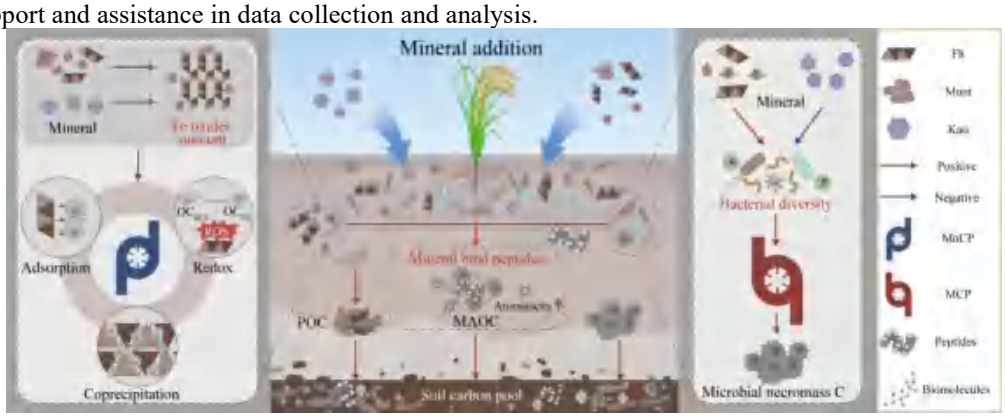
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## ABSTRACT

Mineral-associated organic carbon (MAOC) constitutes a crucial and stable fraction of soil organic carbon (SOC), yet its formation is regulated by minerals with distinct properties and varying capacities to bind organic carbon (OC). Although the influence of mineral type on MAOC is recognized, the underlying mechanisms remain inadequately understood. In this study, pot experiments were used to assess the influence of three soil minerals (montmorillonite, ferrihydrite, and kaolinite) on the quantity and composition of SOC fractions and the structure of bacterial communities. Mineral additions increased MAOC contents by 14% to 42%, accelerated O-alkyl C degradation, and enhanced recalcitrant alkyl C and aromatic C sequestration. The mineral treatments preserved OC by enhancing Fe minerals rather than expanding the surface area of MAOC. Synchrotron radiation–based Fourier transform infrared spectroscopy revealed that montmorillonite and ferrihydrite strengthened the interactions between clay minerals, Fe oxides, and microbial-derived peptides, whereas kaolinite weakened those associations. Furthermore, nano-scale secondary ion mass spectrometry provided direct evidence that montmorillonite and ferrihydrite enhanced spatial coupling between soil C and minerals, in contrast to kaolinite. Additionally, all three treatments significantly increased bacterial community diversity and altered community composition, primarily shifting the relative abundances of dominant phyla *Firmicutes*, *Proteobacteria*, and *Bacteroidota*. These findings elucidate mineral-specific pathways through which soil minerals regulate OC stability and offer a scientific basis for designing management strategies to enhance SOC sequestration.

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# Model Ecosystems as Scalable Pathways for Soil Carbon Sequestration, Productivity and Climate-Smart Land Restoration in Africa

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## ABSTRACT

Despite widespread land degradation land-use change across African ecosystems, depth-resolved evidence monitoring ecosystems that stabilize soil organic carbon (SOC), sustain crop productivity and remain chemically safe remains limited. This study quantifies SOC stabilization mechanisms, nutrient dynamics, heavy metal safety and crop productivity across model ecosystems in Africa. We applied stratified soil sampling across depths (≤150 cm), physical SOC fractionation, greenhouse gas flux measurements, heavy metal analyses, crop yield assessments and long-term chronosequence comparisons across multiple sites and land-use systems. Cocoa agroforestry showed an initial 18 % SOC decline after forest conversion, followed by recovery to 121 Mg C $ha^{-1}$ after 45 years, with cocoa aged ≥18 years exceeding forest SOC at 20–60 cm depth, while maintaining bulk densities below critical thresholds. Forest islands stored up to 200 Mg C $ha^{-1}$ and 15 Mg N $ha^{-1}$ at 0–30 cm depth, with trees enhancing particulate organic matter and aggregate-protected carbon near canopies. Findings in soil organic carbon pools including dissolved organic carbon, particulate organic matter, silt + clay, sand + stable aggregates and recalcitrant SOC fractions ($R_{SOC}$) in the forest islands, natural savannas and smallholder farms across West Africa generally reflected the complex interplay among vegetation shifts, climatic controls, soil properties and human factors on carbon and nitrogen dynamics. Croplands in African dark earths (AfDEs) in Ghana at the 0–10 cm depth stored higher SOC stocks (20–50 Mg C $ha^{-1}$) than non-AfDE croplands (8–27 Mg C $ha^{-1}$), with 53–89 % of carbon stabilized in mineral-associated pools and cumulative $CO_2$ emissions representing <2 % of stored carbon. Except for Hg, Mn, Zn, Cd, As, Pb and Ni remained below USEPA thresholds. The AfDEs produced higher maize yields without fertilizer inputs (≈2.60 t $ha^{-1}$ grain; ≈4.07 t $ha^{-1}$ stover). Near these scalable ecosystems, the CarbonXtras Project is current deploying near-real-time carbon monitoring sensors in Ghana to support low-emission practices through regenerative practices and market premiums. Together, these ecosystems will underpin regenerative and climate-smart land restoration in Africa.

**Keywords:** SOC dynamics, African dark earths, Cocoa agroforestry, Climate-smart land restoration and Greenhouse gas monitoring.

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# Arbuscular Mycorrhizal Fungi Strengthen Aggregate Protection and Reactive Fe/Al Pools to Stabilize Soil Organic Carbon in Acidic Soils

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**ABSTRACT**

Acidic-soil organic carbon (SOC) stability is controlled by two key pathways: (1) physical occlusion within soil aggregates and (2) mineral protection through SOC binding to Fe/Al (hydr)oxides. Arbuscular mycorrhizal fungi (AMF) may reshape both pathways via hyphal networks and the production of binding organic substances. However, their net effect and dominant mechanisms in acidic environments remain unclear. Here we used an acidic soil and established a controlled experiment that separated root and hyphal pathways. We quantified aggregate size distribution and SOC partitioning among aggregate fractions, and we assessed the physical protection of SOC by aggregates using incubation-based mineralization. In parallel, we measured mineral-associated organic carbon and multiple operationally defined Fe and Al pools to track coupled changes in structural and mineral protection.

Our results show that AMF reduced the proportion of microaggregates and increased the formation of large aggregates, indicating improved aggregate stabilization. In line with these structural changes, reactive pools of Fe and Al increased under AMF. Specifically, oxalate-extractable aluminum (Al_o) and oxalate-extractable iron (Fe_o) increased, and the ratios Al_o/Al_d (Alo relative to dithionite-extractable aluminum, Al_d) and Fe_o/Fe_d (Fe_o relative to dithionite-extractable iron, Fe_d) also increased. These patterns suggest a greater contribution of short-range-order Fe/Al phases and/or stronger organo-mineral associations.

Incubation results further indicate stronger physical protection of SOC in AMF treatments. When aggregates remained intact, SOC mineralization rates and cumulative $CO_2$ emissions were lower than in the non-AMF treatment. After aggregate disruption, differences among treatments became much smaller. This pattern indicates that AMF enhances aggregate formation and occlusion, reduces carbon accessibility, and suppresses mineralization. Overall, AMF caused coordinated shifts toward stronger aggregate occlusion and larger reactive Fe/Al pools. These results support a coupled mechanism in acidic soils, where structural and mineral protection jointly enhance SOC stabilization, and provide a testable framework for mycorrhiza-mediated SOC persistence.

**Keywords:** Arbuscular mycorrhizal fungi (AMF), Soil aggregates, carbon stabilization, Fe/Al (hydr)oxides, Mineralization incubation

# Black Carbon Accelerates Soil Carbon Loss through Coupled Iron Redox Cycling

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## ABSTRACT

Black carbon (BC) is widely recognized for its potential to enhance soil carbon (C) sequestration, yet its influence on soil C dynamics remains complex and context-dependent. In this study, we demonstrate that BC can paradoxically accelerate $CO_2$ emissions in upland soils through coupled iron (Fe) redox cycling. Under aerobic conditions, BC promotes abiotic oxidation of Fe(II) to Fe(III), enhancing the decomposition of native soil organic C. Conversely, under anaerobic conditions, BC functions as an electron shuttle, stimulating microbial Fe(III) reduction and further accelerating C mineralization. To investigate the role of mineralogical context, soils were amended with either ferrihydrite or goethite, with or without BC. Comparative analysis revealed that the type of Fe mineral critically modulates the magnitude of BC-induced C loss, with ferrihydrite exhibiting a stronger response due to its higher reactivity.Mechanistic investigations integrated multiple scales of evidence. Soil chemistry analysis showed dynamic changes in Fe speciation, while enzyme assays revealed enhanced activities of C- and Fe-related enzymes. Measurements of soil electron transfer capacity and free radical generation indicated that BC facilitates both abiotic redox reactions and microbial respiration. Microbial community profiling and gene expression analysis further confirmed that BC enriches Fe-reducing bacteria and upregulates key genes involved in anaerobic iron reduction, establishing a direct link between microbial metabolism and enhanced C turnover. Collectively, these results demonstrate that BC accelerates soil C mineralization through a combination of abiotic Fe oxidation, microbial Fe reduction, and enhanced electron transfer processes. This study challenges the conventional view of BC as a persistent carbon sink in soils, highlighting its potential to increase C emissions under specific mineralogical and redox conditions. Our findings underscore the critical importance of considering Fe mineral type and redox status when evaluating BC amendments for soil C management. By providing a multi-scale mechanistic understanding of BC-induced soil C dynamics, this work informs both fundamental research on soil biogeochemistry and practical strategies for carbon sequestration and climate mitigation.

# Effects of Human Land Use Practices on the Binding Patterns of Organic Carbon and Iron Oxides

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**ABSTRACT**

As the largest carbon reservoir in terrestrial ecosystems, soil plays a crucial role in the global carbon cycle. Among its processes, soil organic carbon (SOC) binds with iron oxides (Fe) through chelation, aggregation, or coprecipitation, forming a key mechanism for long-term, stable soil carbon sequestration. However, it remains unclear how different human land-use activities and increasing years of cultivation alter the binding patterns of carbon and iron in soils.Therefore, this study employs the C/Fe molar ratio to characterize the coupling patterns between soil organic carbon and iron oxides. soil profiles were collected from sequences under different land-use practices and varying cultivation durations. The study characterized the distribution patterns of C/Fe molar ratios across these sequences, elucidating how land-use practices and cultivation duration influence the binding mechanisms between organic carbon and iron oxides. This provides scientific data and theoretical foundations for understanding soil carbon-iron coupling mechanisms under human land-use impacts. The results indicate:

(1) Under different land use types, compared to undisturbed buried ancient laterite (ranging from 0.09 to 0.57), the C/Fe molar ratio increased in forested land (0.19–1.90) and cultivated land (0.08–0.75), while it slightly decreased in sparse woodland and grassland (0.06–0.53) and grassland (0.07–0.44). Furthermore, the C/Fe molar ratio in the topsoil layer was significantly higher than that in the subsoil layer.

(2) Under different cultivation durations, compared to undisturbed buried ancient laterite (0.024–0.057), the C/Fe molar ratio decreased in ancient laterite cultivated for 5 years (0.022–0.027), while those of ancient laterite cultivated for 80 years and 400 years showed slight increases (ranging from 0.027 to 0.059 and 0.028 to 0.070, respectively), exhibiting a trend of initial decrease followed by increase over time.

(3) In summary, under different land use regimes, forested and cultivated soils exhibit stronger adsorption-based binding mechanisms. Specifically, the carbon-iron binding mode in forested surface soils transitions to a combined adsorption and coprecipitation mechanism, while open woodlands with weeds and weed-dominated areas demonstrate weaker adsorption-based binding. Across different cultivation durations, ancient laterite soils cultivated for 400 years and those cultivated for 80 years exhibited stronger adsorption intensity than those cultivated for 5 years. Human land use activities caused fluctuations in the adsorption strength of cultivated land, but the carbon-iron binding mode remained predominantly adsorptive.

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# Divergent stabilization controls of lignin phenols and amino sugars as biomarkers for soil organic carbon source

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## ABSTRACT

Biomarkers are biogenic compounds widely used to trace the origin, composition, and stabilization of soil organic carbon (SOC). Among them, lignin phenols (LGs) and amino sugars (ASs) are commonly applied as indicators of plant- and microbial-derived C, respectively. However, selective transformation and preservation of these biomarkers can decouple their abundance from original source inputs, thereby constraining their quantitative interpretation. A mechanistic understanding of the factors governing the stabilization of LGs and ASs is therefore essential for their robust application in SOC research. To address this knowledge gap, we analyzed cropland soils from East China to investigate the selective preservation of LGs and ASs and to identify their dominant controlling factors.

Both LG and AS concentrations were positively correlated with SOC contents, whereas LG:SOC ratios declined with increasing SOC. Variation in LG:SOC ratios was primarily associated with lignin molecular composition and functional group characteristics, indicating that intrinsic molecular properties regulate LG persistence. In contrast, AS:SOC ratios were strongly governed by non-crystalline minerals, highlighting the dominant role of mineral protection in the stabilization of microbial necromass. Climate variables, including annual precipitation, mean temperature, and their seasonality, emerged as primary controls of AS:SOC ratios, likely through indirect regulation of non-crystalline mineral formation. These findings highlight the molecular control of LGs and climate-mineral regulation of ASs.

These divergent stabilization controls indicate that LGs predominantly reflect relatively recent plant inputs whose retention depends on molecular traits, whereas ASs trace long-term stabilization of mineral-associated microbial C. Recognition of these contrasting stabilization pathways is essential for the prudent quantitative estimation of plant- and microbial-derived SOC using the two biomarkers.

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# Chemical pathways of soil organic carbon stabilization in Mediterranean soils

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**ABSTRACT**

Mediterranean agroecosystems are characterized by high vulnerability of soil organic carbon (SOC) due to shallow profiles, intense mineralization, and increasing climatic stress. While organic amendments are widely promoted to enhance SOC stocks, the mechanisms governing short-term carbon stabilization across soil matrix remain insufficiently understood, particularly in perennial systems established on Leptosols.

This study evaluates three consecutive years of SOC dynamics following the application of olive pomace compost as a nature-based solution in a traditionally managed olive grove (Olea europaea L.) in northeastern Portugal. Compost was applied at increasing rates (0, 10, 20, and 40 t $ha^{-1}$), and SOC responses were assessed through a molecular–physical framework integrating bulk SOC, density-based fractionation into free particulate organic matter (fPOM), occluded particulate organic matter (oPOM), and mineral-associated organic matter (MAOM), together with aggregate stability measurements and soil chemical characterization.

Results demonstrate a clear dose-dependent increase in SOC, with the highest application rate sustaining carbon accumulation over the three-year monitoring period. Fractionation analyses indicate that initial SOC gains were dominated by increases in particulate pools (fPOM and oPOM), reflecting rapid incorporation of compost-derived carbon, presenting a 17.11 g $kg^{-1}$ on year 1 of monitoring, with a further decrease to 8.69 g $kg^{-1}$ on year 3 at the highest application dosage, while control group presented an standardized average of 7.65 g $kg^{-1}$. However, over time, a progressive redistribution of carbon towards the MAOM fraction was observed, specially at high dose of compost application, a relative value of 43.7 % on first year followed by 46.4 % and 55.7 % of MAOM, respectively for year 2 and 3, suggests an early shift transition from labile carbon inputs to physically and chemically protected SOC pools, even within the short-term timeframe. Furthermore, aggregate stability results suggest that physical occlusion within aggregates followed by enhanced cation exchange capacity and base saturation indicates that compost-derived organic ligands promoted stronger associations between organic compounds and mineral surfaces, reinforcing MAOM formation.

Overall, the findings demonstrate that olive pomace compost contributes to SOC stabilization through coupled biochemical and physical mechanisms, rather than solely by carbon input. This study provides field-based evidence that short-term organic amendment strategies can initiate stabilization pathways in Mediterranean Leptosols, highlighting the relevance of aggregate-mediated protection for sustaining soil carbon under climate-vulnerable conditions.

# Into the Unknown: A Continental Exploration of Viral Diversity in Australian Soils

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**ABSTRACT**

Soil viruses play a pivotal role in regulating microbial population dynamics and metabolic activities, thereby influencing carbon, nutrient, and biochemical cycling within terrestrial ecosystems. Despite being the most abundant biological entities on Earth, soil viruses remain poorly characterised. To address this knowledge gap, we conducted the first continental-scale investigation of soil viromes across Australia. Topsoil samples (0–10 cm) were collected within the 500–600 mm annual rainfall zone using a paired sampling design that compared land-use types within the same soil classification. Sampling spanned three major transects: (1) a South–North transect along the east coast (36.58° S–21.01° S), (2) an East–West transect across northern Australia (146.04° E–121.93° E), and (3) a 1,200 km transect across agricultural landscapes in the southwest. Whole-genome metagenomic sequencing revealed that DNA viral reads constituted less than 1% of total sequences but exhibited strong spatial heterogeneity across the continent. We identified a high diversity of novel viral taxa, with phages accounting for approximately 80% of viral sequences and Lenarviricota emerging as a dominant microbe-associated lineage. Integration of viral, bacterial, and fungal datasets indicated that soil viruses exert substantial regulatory control over microbial communities, potentially influencing ecosystem functioning. This study establishes the first continental-scale baseline of soil viral diversity and distribution in Australia, providing crucial insights into viral ecology and a foundation for predicting the impacts of soil viruses on ecosystem health and agricultural sustainability.

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# Biogeographic patterns and drivers of soil viromes

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**ABSTRACT**

Viruses are key mediators of soil microbial function and are an important component of soil ecosystems, yet existing studies of soil viromes are limited in spatial scale and biome coverage. Here, we present a comprehensive synthesis of soil virome biogeographic patterns based on the Global Soil Virome dataset (GSV) retrieved from 1,824 soil metagenomes across the globe. The GSV comprises 80,750 partial genomes of DNA viruses, of which 96.7% are taxonomically unassigned. The biogeography of soil viral diversity and community structure vary across different biomes. Interestingly, the diversity of viruses does not align with the diversity of microbial community, particularly showing low levels in forest and shrubland soils. We demonstrated that soil texture and moisture conditions are the primary factors that differentiate soil viral diversity. This is further supported by our predicted soil viral diversity atlas, which reveals higher diversity in humid and subhumid regions. Additionally, binomial degree distribution pattern suggests a random co-occurrence pattern of soil viruses. These findings provide a valuable resource for elucidating the ecology of soil viral communities and are crucial for their comprehensively incorporation into soil ecosystem models.

# Rhizosphere-triggered viral lysogeny mediates microbial metabolic reprogramming to enhance arsenic oxidation

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**ABSTRACT**

The rhizosphere is a critical hotspot for metabolic activities involving arsenic (As). While recent studies indicate many functions for soil viruses, much remains overlooked regarding their quantitative impact on rhizosphere processes. Here, we analyze time-series metagenomes of rice (*Oryza sativa* L.) rhizosphere and bulk soil to explore how viruses mediate rhizosphere As biogeochemistry. We observe the rhizosphere favors lysogeny in viruses associated with As-oxidizing microbes, with a positive correlation between As oxidation and the prevalence of these microbial hosts. Moreover, results demonstrate these lysogenic viruses enrich both As oxidation and phosphorus co-metabolism genes and mediated horizontal gene transfers (HGTs) of As oxidases. *In silico* simulation with genome-scale metabolic models (GEMs) and *in vitro* validation with experiments estimate that rhizosphere lysogenic viruses contribute up to 25% of microbial As oxidation. These findings enhance our comprehension of the plant-microbiome-virome interplay and highlight the potential of rhizosphere viruses for improving soil health in sustainable agriculture.

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# Twenty-Year Time Series Reveals Ecological and Evolutionary Dynamics of Viruses in a Freshwater Lake

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**ABSTRACT**

This study leveraged 20 years of monitoring data from Lake Mendota to investigate viral ecological and evolutionary dynamics using metagenomic and metatranscriptomic analyses. Over 1.3 million viral genomes were analyzed to reveal patterns driven by temporal, seasonal, and environmental changes. More than 140,000 viral auxiliary metabolic genes (AMGs), involved in carbon, nitrogen, and sulfur cycling, were identified across a broad range of functional categories. High-abundance AMGs such as *psbA*, *pmoC*, and *katG* showed stable distributions and displayed two distinct patterns: "broad host" and "narrow host". Broad host AMGs, less influenced by environmental variability, were involved in sulfur metabolism and folate synthesis, while narrow host AMGs targeted specific host functions—for example, photosynthesis gene *psbA* in cyanophages, and *gnd* and *zwf* related to the pentose phosphate pathway. The study uncovered correlations between virus-host interactions and seasonal changes, along with ecological niche differentiation. High-frequency viral populations exhibited both gene-specific and genome-wide selection. This included positive selection of adaptive genes, temporal reduction in genome-wide SNP heterogeneity, and the emergence of dominant subpopulations with enhanced replication and transcriptional regulation capacities. These dominant viruses—termed “royal family” viruses—maintain ecological stability and dominance through genomic evolution, consistent with the "kill-the-winner" model. Additionally, viral abundance was linked to environmental variables such as inorganic carbon and ammonium, highlighting complex interactions between nutrient availability and predator-prey dynamics.

**Keywords:** Viral ecology; Viral evolution; Time-series; Freshwater lake

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# Viral cooling of $N_2O$ emissions in long-term acidified soils

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## ABSTRACT

Soil viruses are increasingly recognized as key agents in biogeochemical cycling, yet their evolutionary dynamics and regulatory roles under long-term environmental acidification remain poorly understood. Using an integrated approach that combines $D_2O$-labeled Raman spectroscopy, $^{15}N$ isotope tracing, metagenomic sequencing, and machine learning models on 18-year acidified soils, we demonstrate how virus-host co-evolution shapes $N_2O$ emissions. Our results reveal that long-term acidification drives convergent evolutionary trajectories in both denitrifiers and viruses, characterized by genomic streamlining and functional specialization. While microbial hosts transitioned to stress tolerance life history strategies, viruses evolved enhanced regulatory capacity through specialized gene arsenals and morphological adaptations. Machine learning modeling identified host defense capacity as the primary driver of virus-denitrifier interaction outcomes, facilitating viral pruning that optimizes denitrifying community structure. Crucially, virus addition experiments uncovered a previously unrecognized dual regulatory mechanism: while neutral soils exhibited a conventional 'quantity-driven' mode through increased *nosZ* gene (nitrous oxide reducing gene) abundance, acidic soils displayed a novel 'efficiency-optimization' mode that enhanced $N_2O$ reductase activity by 33.2% without altering genetic potential. Our study establishes viruses as co-evolutionary partners that develop sophisticated regulatory mechanisms under persistent environmental stress, offering novel insights for managing $N_2O$ emissions in acidified soils.

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# Soil viruses as key regulators of carbon sequestration and plant growth

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**ABSTRACT**

Soil viruses are increasingly recognized as pivotal agents in terrestrial biogeochemical cycles; however, their context-dependent roles in modulating soil organic carbon (SOC) dynamics remain inadequately characterized. Through integrated lab- and field-scale experiments, we investigated how environmental cues influence viral life-history strategies, specifically, the transition between lytic and lysogenic cycles, and their consequent effects on microbial turnover, nutrient cycling, and carbon sequestration. Our findings reveal that viral life-history strategies are highly responsive to environmental conditions. Nutrient-rich environments, such as those amended with long-term manure or labile carbon inputs, promote lytic dominance. This shift accelerates microbial turnover and necromass accumulation via the "viral shunt," whereby host cell lysis releases labile nutrients, including dissolved organic carbon (DOC) and nitrate. These nutrients not only stimulate the enrichment of fast-growing bacterial taxa but also enhance plant growth, as demonstrated in soybean rhizosphere experiments in which prophage induction with mitomycin C significantly boosted root development. Beyond immediate nutrient release, viral activities exert broad ecological influence. Microcosm studies involving direct manipulation of viral abundance revealed that viral predation restructures microbial communities and alters their functional gene profiles, thereby reducing $CO_2$ and $N_2O$ emissions. More importantly, this top-down control enhances microbial carbon use efficiency and accelerates community turnover, resulting in substantial accumulation of microbial necromass. These virus-mediated processes are strongly context-dependent. While lytic activity may elevate $CO_2$ emissions in SOC-poor soils, it promotes necromass stabilization and SOC accrual in organically enriched environments. Under nutrient-limited or drought-stressed conditions, the lysogenic viruses and viral auxiliary metabolic genes (AMGs) become enriched, suggesting a "metabolic rescue" strategy that supports host persistence under stress. An emerging virus-mediated microbial carbon pump (MCP) framework connects these dynamics, highlighting viral lysis and AMG-driven metabolic reprogramming as key mechanisms underlying SOC persistence. Together, our results position soil viruses as central regulators of carbon cycling, linking microbial mortality to both plant vitality and long-term soil carbon storage. These insights underscore the potential of leveraging viral community dynamics through targeted organic amendments to achieve climate-resilient soil management.

# Microbial Community Succession in the Rhizosphere of Citrus Grandis Exocarpium in Response to Fertilization and Huanglongbing Stress

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## ABSTRACT

**Overview:** *Candidatus Liberibacter* asiaticus (CLas) is the causative agent of Huanglongbing (HLB), a deadly disease that affects citrus output globally. Although the rhizosphere microbiome is essential for plant health and disease resistance, little is known about how long-term fertilization controls microbiome assembly in medicinal citrus root and soil compartments and how this is related to the occurrence of HLB. Few studies have combined multi-year, multi-compartment microbiome dynamics with host metabolomics and pathogen response in citrus, despite earlier research highlighting the general advantages of organic fertilizers (OF) on soil microbial diversity and plant growth.

**Method:** We investigated the bacterial and fungal communities in the bulk soil, rhizosphere, and endosphere of *Citrus Grandis Exocarpium* (Huajuhong) after 1, 3, and 5 years of continuous OF or chemical fertilizer (CF) application using amplicon sequencing and co-occurrence network analysis. Metabolomic analysis assessed subsequent effects on plant medicinal quality (Fig. 1).

**Result:** OF enhanced microbial α-diversity and network stability. Bacterial communities dominated network interactions and showed clear temporal succession, with OF enriching beneficial taxa like *Burkholderia*, while CF reduced pathogenic *Fusarium* abundance. Surface soils showed higher network complexity, indicating functional stratification along soil depth. The highest CLas infection was in 5-year trees, indicating prolonged HLB stress impaired the endophytic microbiome—an effect mitigated under OF. Metabolomics revealed OF broadened the spectrum of bioactive compounds, whereas CF elevated specific flavonoids and polysaccharides.

**Discussion:** Our findings demonstrate that fertilization regimes drive distinct successional trajectories in the rhizosphere microbiome. Under HLB stress, plants become more susceptible to secondary infections. Although OF promotes a stable and diverse microbiome, associated risks such as antibiotic resistance genes warrant careful assessment. This study offers a microecological foundation for designing integrated fertilization and probiotic strategies to enhance systemic disease resistance in citrus.

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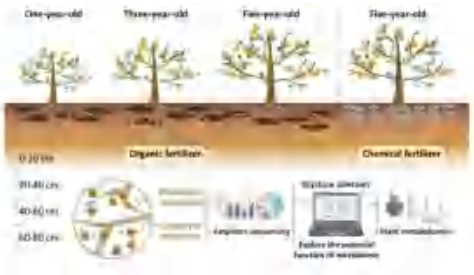



Fig.1 Schematic diagram of the study design

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# Translational profiles reveal prokaryotic resource allocation to prophages

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**ABSTRACT**

Prophages integrated within prokaryotic genomes are key drivers of microbial community dynamics. However, current methods such as (viral) metagenomics, metatranscriptomics, and induction assays cannot capture active translation *in situ*, the critical step that reflects direct metabolic investment. Here, we apply metaRiboSeq, i.e. metatranslatomics, to quantify how prokaryotes allocate translational resources to their prophages at the community level across diverse microbiome types. We recovered metagenome-assembled genomes (MAGs) from soil, marine, and human samples, representing free-living and host-associated environments. By mapping ribosome-protected mRNA fragments to prophage regions within MAGs, we quantified what fraction of host translational activity is devoted to prophage genes, and how that investment is distributed among lysogeny maintenance, lytic, and auxiliary metabolic genes. We hypothesize that prophage translational burden and investment strategies differ across ecosystems, reflecting variation in environmental conditions. Thus, metaRiboSeq is a powerful tool for resolving phage translational activity *in situ* and provides a quantitative framework for understanding how prokaryotes allocate resources to their prophages.

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# Virus-prokaryote interactions assist pollutant removal in constructed wetlands

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**ABSTRACT**

Constructed wetlands (CWs) are widely used as a sustainable technology for wastewater treatment, yet the role of viruses within their microbial communities remains largely unexplored. In this study, two pilot-scale horizontal subsurface flow CWs were established to examine viral community dynamics under different hydraulic loading rates (HLRs), using in-depth metagenomic analysis. Gene-sharing network analysis revealed that CWs harbor a high proportion of novel viral lineages, with over 99% of viral operational taxonomic units not clustering with known References genomes. Notably, a subset of core viruses, dominated by families such as *Siphoviridae* and *Podoviridae*, persisted across different compartments and conditions, suggesting their potential ecological importance. HLR significantly influenced the assembly of viral communities, with higher diversity and niche breadth observed under elevated HLR conditions, particularly in the substrate layer. Similar dynamics between viral and prokaryotic communities were identified, indicating coordinated responses to hydrological variations. Importantly, viruses were found to interact closely with functional prokaryotes involved in key nutrient-cycling processes. Through CRISPR-based host prediction, we demonstrated that viruses could infect microorganisms responsible for denitrification and ammonia oxidation. Furthermore, viral auxiliary metabolic genes (AMGs) associated with sulfur and nitrogen cycling were detected, with sulfur-related AMGs notably enriched under higher HLR. These findings reveal the significance of viruses in pollutant removal in CWs and enhance the understanding of the relationship between engineering design parameters and performance from microbial perspectives.

**Keywords:** constructed wetlands; virus-prokaryote interactions; hydraulic loading rate; metagenomics; wastewater treatment

# Ciprofloxacin- driven purifying selection on viral genomes accelerates soil $N_2O$ production

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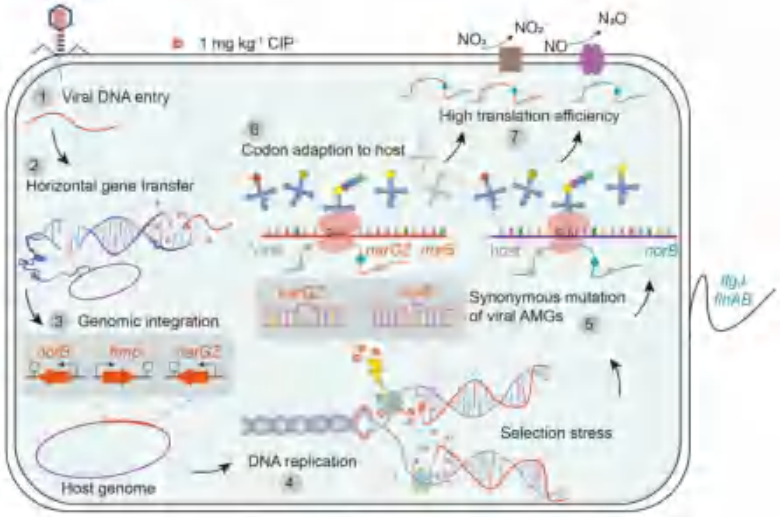
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## ABSTRACT

Viruses are ubiquitous regulators of microbial dynamics and may thus greatly influence global microbial- driven greenhouse gas emissions. Anthropogenic stressors, such as chemical contamination, are likely to amplify these viral contributions; however, their global significance and underlying mechanisms remain elusive. Utilizing $^{15}N$ tracing, metagenomics, and laboratory assays, we explore soil viral communities and their evolutionary potential under the stress from antibiotic ciprofloxacin (CIP), focusing on their roles in regulating nitrogen cycling and $N_2O$ production. Through isolation and reinoculation of soil viruses, we demonstrate that CIP stimulates soil denitrification- derived $N_2O$ production, with 18 to 29% of the increase attributed to viral activity. Under CIP stress, soil viruses shift toward a lysogenic lifestyle, promoting mutualism with denitrifiers by horizontally transferring viral denitrification- related auxiliary metabolic genes (AMGs). The observed synonymous mutations in these AMGs, driven by CIP, suggest enhanced purifying selection, likely optimizing codon usage to align with host pReferences. This optimization likely enhances the expression of denitrifying AMGs and increases $N_2O$ production. This study provides insights into the overlooked role of viral dynamics and genomic mutations in modulating $N_2O$ production under stressful environments, highlighting their evolutionary significance and impact on biogeochemical cycles in the Anthropocene.

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**The conceptual model of metabolic functions of host and their interactions with viruses under CIP exposure**. The lysogenic viruses expand the metabolic potential of host denitrifiers via horizontally transferring AMGs, which undergo purifying selection to align codon usage with host, eventually raising $N_2O$ production under CIP stress.

# Interactive dynamics between rhizosphere bacterial and viral communities facilitate soybean fitness to cadmium stress revealed by time-series metagenomics

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## ABSTRACT

**[Objective]** The distinctive symbiotic relationship between rhizobacteria and soybean (Glycine max) can enhance soil fertility and assist soybean defense heavy metal stress, such as cadmium (Cd), in soils. Soil viruses are critical for modulating microbial activities and enhancing host adaptability to soil contamination by encoding auxiliary metabolic genes (AMGs). However, the community structure, functional diversity and ecological roles of soil viruses and their dynamic interactions with soil-dwelling microbes under Cd stress remain unclear. Here, we characterized the bulk and rhizosphere bacterial community in a Cd-contaminated soybean field at five growth stages and investigated the rhizosphere microbial functional traits and the viral community after flowering using metagenomics. We showed that the rhizosphere bacterial community exhibited a stronger soybean development- dependent diversity pattern relative to bulk soil and had a more critical role in predicting Cd accumulation. The relative abundance of Actinobacteria in the rhizosphere increased with soybean development, particularly in the families *Nocardioidaceae* and *Intrasporangiaceae*, which were further identified as the main contributors of amino acid transport E and secondary metabolites Q genes. Viral analysis suggested an interactive and complementary assembly between viral and bacterial communities. Importantly, viruses exhibited a broader host range during the flowering period, and infected specific functional taxa such as *Bradyrhizobium* and *Nocardioides*, highlighting their potential impact on the rhizobia-soybean symbiosis and soybean growth and fitness. Furthermore, AMGs related to element cycling and microbial metabolism were identified and functionally and phylogenetically characterized, suggesting the contribution of these virus-encoded genes to biogeochemical cycles and soybean fitness under Cd stress. Together, our results expand our understanding of the ecological functions of rhizosphere viruses in Cd pollution-stressed soils, and provide insights in developing new strategies for bioremediation of contaminated soils.

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# Soil virome dynamics and ecological regulation during revegetation of rare earth tailings

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**ABSTRACT**

Rare earth element (REE) mining causes severe soil degradation and disrupts microbially mediated carbon cycling, yet the role of soil viruses during ecosystem recovery remains largely unexplored. Here, we investigated how long-term revegetation reshapes soil viromes and regulates microbial carbon processing in REE tailings. Using an eight-year vegetation restoration chronosequence, we combined 16S rRNA amplicon sequencing, shotgun metagenomics, viral genome reconstruction, virus–host linkage analyses, and structural equation modeling to elucidate virus-mediated mechanisms underlying soil recovery.

Vegetation restoration markedly improved soil quality, increasing organic carbon, nutrient availability, microbial biomass, and extracellular enzyme activities. Concomitantly, viral communities exhibited higher diversity and a pronounced shift from lysogenic to lytic lifestyles. Viral community composition closely tracked bacterial community succession, and virus–host associations revealed active viral control over dominant bacterial taxa involved in complex carbon degradation. Lysogenic viruses in unrestored tailings encoded diverse auxiliary metabolic genes (AMGs) related to carbohydrate, amino acid, and energy metabolism, whereas AMG abundance declined with increasing soil quality, indicating reduced viral metabolic supplementation under nutrient-rich conditions.

Partial least-squares path modeling identified viral life-strategy transitions as a central mechanistic bridge linking revegetation to soil quality enhancement. Vegetation-driven nutrient enrichment induced a lysogenic-to-lytic switch, strengthening top-down viral regulation of bacterial communities and stimulating extracellular enzyme activities. This process enhanced microbial turnover and carbon processing through a soil “viral shunt,” whereby viral lysis releases microbial biomass and intracellular substrates that fuel heterotrophic decomposition.

Our findings demonstrate that soil viruses act as keystone regulators coupling aboveground revegetation with belowground carbon cycling during REE tailings restoration. By integrating viral dynamics into restoration ecology, this study extends the viral shunt concept to terrestrial reclamation systems and highlights soil viromes as critical, yet overlooked, drivers of ecosystem recovery.

# Impact of Warming and Fertilization on Viral Communities in Agricultural Soils

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**ABSTRACT**

Soil viruses are highly abundant and serve as key modulators of microbial population dynamics and soil ecological processes. Anthropogenic environmental changes, including those driven by climate and land use, are reshaping soil ecosystems; however, their impact on the often-overlooked soil virome remains poorly understood. In this study, a field mesocosm experiment was used to investigate the influence of a warmer, drier climate regime—including its legacy effects—on soil viral communities under contrasting fertilization treatments (manure vs. urea). Results showed that both warming and fertilization significantly altered the composition of soil viral and bacterial communities. Notably, warming and fertilization substantially enriched viral-encoded auxiliary metabolic genes (AMGs) related to carbon cycling. These viral AMGs may be transferred to microbial hosts, thereby directly mediating biogeochemical cycles. Viral AMGs could modulate host metabolism during infection, potentially influencing biogeochemical cycling. Furthermore, fertilization interacted with climatic factors to regulate the abundance of specific viral taxa and shape host-virus interaction networks. Collectively, these findings provide novel insights into the shaping of soil viromes by climate change and underscore the significant ecological roles of viruses in influencing host dynamics and biogeochemical cycling.

# How do soil viruses exert impacts on the soil carbon cycle under anaerobic? The ubiquitous but neglected part

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**ABSTRACT**

Anaerobic oxidation of methane (AOM) has the potential to mitigate global warming by converting $CH_4$ either to $CO_2$ or to soil organic carbon (SOC) stored in soils. However, it remains unclear whether soil viruses affect the AOM process and carbon sequestration. In addition, viruses have two major life cycle states (i.e. lytic and lysogenic) that can differentially reprogramme the host metabolism. How and to what extent viruses in different life states influence the AOM process remains elusive. To address this knowledge gap, we used $^{13}C$ tracing to compare the effects of mitomycin C-induced and free extracellular viruses on anaerobic methane oxidation. In this study, we first demonstrated that the inoculation of mitomycin C-induced viruses functioned as prophages, resulting in distinct effects on AOM compared to free extracellular viruses. Specifically, both mitomycin C-induced and free extracellular viruses enhanced $CH_4$-derived carbon sequestration in soil. However, the free extracellular viruses could increase 60.42 Mg SOC and 8.58 Mg Fe-bound organic C $d^{-1}$ globally through viral lysis and increase carbon affinities to iron oxides. The mitomycin C-induced viruses could increase the daily amount of 28.5 Mg SOC, but decrease 19.6 Mg Fe-bound organic C globally, by improving the survival of associated microbes to promote the AOM process. This work demonstrates for the first time that inoculation with mitomycin C-induced viruses provides a novel approach to directly quantify the effects of lysogenic cycle viruses on soil functions and the contributions of viruses in two different life cycles, lytic and lysogenic, to soil carbon sequestration under anaerobic conditions. These results complement the 'viral shuttle' mechanism in soils and provide a new understanding of the impact of viruses on soil carbon sequestration.

**Keywords:** Soil virus; Fe-bound OC; Viral life cycle; Anaerobic oxidation of methane; Soil carbon sequestration

# Rhizosphere phage–host interactions drive crop rotation-enhanced disease suppressiveness

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**ABSTRACT**

Against the backdrop of intensive agricultural production, continuous monocropping readily induces a suite of replant obstacles, which represent a critical limiting factor for both the yield and quality of crops. In the cultivation of peanut (*Arachis hypogaea* L.), one of China's foremost oil and economic crops, continuous cropping phenomenon are prevalent nationwide. The high incidence of soil-borne diseases is a defining hallmark, especially the occurrence of bacterial wilt—a globally important plant disease caused by *Ralstonia solanacearum*.

Crop rotation is promoted widely as a sustainable solution to alleviate replant obstacles, with resulting benefits to crop health and yield. The enhanced disease suppression capacity of crop rotation has been attributed to the modulation of rhizosphere bacterial community. As highly abundant biological entities in soil, viruses especially phages (viruses of infecting bacteria) have been shown to drive changes in the diversity and composition of bacterial community. Leveraging phage—bacteria host interactions, phages exert a vital regulatory in biogeochemical cycles and are also believed to be applicable to control soil-borne bacterial diseases. However, it remains unclear whether rhizosphere phage communities are involved in rotation-mediated disease suppressiveness, and determining phage—bacteria interactions is crucial for establishing a holistic understanding of rhizosphere microbiome functions.

Based on a 12-year long-term field experiment, coupled with multiomics analysis, we investigated how responses of rhizosphere phages to crop management impacted soil disease suppressiveness. Our results showed that rotation assists peanut to resist bacterial wilt disease by reducing pathogen abundance and constructing beneficial rhizosphere microbial communities, as a consequence of the phage–bacteria synergistic interactions. Phage communities in monocropping and rotation rhizosphere were dominated by phages of potentially beneficial genera and phages of putative pathogens, respectively, with the relative abundance of *Ralstiona*-targeted phages being much higher in rotation rhizosphere (18.05%) than in monocropping rhizosphere (2.83%). The regulation of bacterial communities by phages were also verified by the phage transplantation experiment. Collectively, our findings suggest that crop rotation can serve as a strategy for sustainable agriculture by modulating rhizosphere phage–host interactions to enhance disease suppressiveness.

**Acknowledgments**

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# Extracellular polymeric substances in soil: drivers, functionality and future research directions

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**ABSTRACT**

Most microorganisms on Earth are suggested to surround themselves in a matrix of extracellular polymeric substances (EPS). This EPS matrix fulfils crucial functions for microbial life, such as mitigating environmental stress. Soil microorganisms have a central role in global biogeochemical cycles, and their residues contribute to soil organic carbon. However, despite the central role of microorganisms, the contribution of EPS to these processes and its fate in the soil are still being investigated. It is known that EPS can exhibit properties such as high-water absorption and viscosity, raising questions about its potential applications in agriculture. Yet, our knowledge of drivers, functionality and overall significance of EPS in soil remains still limited.

At the conference, I will share insights from various experiments and field studies conducted in different ecosystems. These studies address the question of how environmental factors influence the composition of EPS. I will also present studies on the potential functionalities of EPS. Furthermore, I will present results from a visualisation approach that quantifies the formation of biofilms within the porous soil network, offering directions for future research. Overall, I will provide a compelling insight into EPS within soil systems and shed light on its potential role in agriculture. This will provide a foundation for discussions about functional significance and ecological relevance, as well as future research directions aimed at improving our understanding of EPS in soil and possible applications.

# Small fractions, large effects: the role of extracellular polymeric substances in soil function

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**ABSTRACT**

Most microorganisms are thought to embed themselves within a matrix of extracellular polymeric substances (EPS). Although EPS can represent only a small, transient fraction of total soil organic matter at any given moment, it can exert outsized control over soil function by regulating micro-scale hydration, adhesion, and biofilm formation. These EPS-mediated processes can, in turn, influence aggregate stability, pore-scale connectivity, diffusion of gases and solutes, and the spatial coupling of microbes with substrates and mineral surfaces. Yet, linking EPS chemistry and physical properties to measurable soil functions remains challenging because EPS is heterogeneous, highly reactive, and difficult to quantify in situ across relevant spatial and temporal scales. In this presentation, I will examine why "small fractions" of EPS can produce "large effects" on soil physical, chemical, and biological functioning. The talk will synthesize current understanding of (i) environmental and management drivers that modulate EPS production and composition, (ii) mechanistic pathways through which EPS alters water retention, viscosity, and soil structural dynamics, and (iii) implications for nutrient cycling and carbon persistence via interactions with minerals and aggregates. I will conclude by outlining methodological and conceptual priorities—particularly approaches that connect pore-scale EPS organization and biofilm architecture to whole-soil performance—aimed at improving predictive understanding of EPS in soils and informing practical strategies to enhance soil resilience under agricultural use.

# Seeing the Invisible: Visualizing Enzymatic Processes in Soil Hotspots

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**ABSTRACT**

Exoenzymes in the soil are crucial to mobilize nutrients, transform pollutants, and maintain soil health. Understanding the spatial and temporal organization, as well as the intensity of biochemical processes in soil hotspots, is essential to unravel soil functioning and nutrient cycling. However, this remains difficult for direct observation.

Soil zymography (Spohn et al., 2013) represents a non-invasive method facilitating the *in situ* visualization and localization of potential enzyme activities in soil. Because of its universality and simplicity, soil zymography imaging has been widely used to visualize the hidden microbial and root life in soil, which is a very heterogeneous and "dark" environment. Our primary focus is to highlight the progress made over last 10 years with respect to the spectrum of enzyme activity imaging, zymography resolution, standardization and hotspot identification (Bilyera and Kuzyakov, 2024). We emphasize the integration of zymography with the visualization of soil acidification (optodes), root exudation and pesticides ($^{14}$C phosphor imaging), fertilizers ($^{33}$P phosphor imaging), nutrients (DGT) and water (neutron imaging) fluxes.

As processes and mechanisms are clearly multifactorial, combining individual approaches is essential to achieve a comprehensive understanding of soil processes. The multi-imaging approach comes with a set of challenges: 1) bridging scales in time (from minutes to days) and space (from µm to cm); and 2) the sequence of method application. The co-localization analysis of such individual images integrates biochemical, physico-chemical and microbial properties, which facilitate a deeper understanding of soil processes and microbial interactions (Banfield et al., 2017; Bilyera et al., 2021).

We present the advancements made in soil zymography, as well as its current applications, challenges and potential integration with other imaging methods. This versatile technique has applications in natural and agricultural ecosystems, in both field settings and laboratory studies, capable of scaling from the entire root system (cm and dm) down to microbial communities (µm).

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# Increased microbial extracellular polymeric substances as a key factor in deep soil organic carbon accumulation

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**ABSTRACT**

Microbial-derived carbon plays a crucial role in mitigating climate change by forming stable carbon components through the soil microbial carbon pump. However, previous studies usually used intracellular carbon (microbial necromass carbon) as a quantitative indicator, ignoring the contribution of extracellular carbon (EPS) as an extracellular metabolite of microorganisms to soil organic carbon (SOC), particularly in deep soils. This study explored the distribution of EPS in six typical soil profiles (0–120 cm) from two parent materials (limestone and shale) and three land use types (dryland, woodland, and paddy land). The contribution of microbial biomass carbon (MBC) to SOC was significantly higher than that of EPS-carbon (EPS-C) in surface soils (0–40 cm), while EPS-C constituted a larger proportion in deeper soils (80–120 cm). The EPS accumulation efficiency (EPS-protein/MBC and EPS-polysaccharide/MBC) gradually increased with soil depth. This accumulation was strongly correlated with the abundance of g_Zixibacteria, g_Zavarzinella, g_Xylohypha, g_Xanthothecium, and g_Xanthagaricus. Data analysis revealed that β-glucosidase (BG) activity and total nitrogen (TN) content had significant negative effects on the EPS/SOC ratio. Additionally, extracellular enzyme analyses confirmed that low nitrogen availability in deeper soils enhanced the EPS accumulation efficiency, thereby increasing the EPS-C/SOC ratio along the soil profile. Overall, this study provides new insights into the composition of deep soil carbon pools and highlights the important role of EPS in deep soil carbon storage.

**Keywords:** Deep soil; Soil organic carbon; Extracellular polymeric substances; Accumulation efficiency; Microbial community; Nutrient limitation

**Acknowledgments**

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# Characterization of compound-specific extracellular polysaccharide biomarkers across soil organisms and plants

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## ABSTRACT

Soil extracellular polysaccharides (EPSac) are important biopolymers in terrestrial ecosystems, playing key roles in soil aggregation, water retention, nutrient cycling, and carbon sequestration. These polysaccharides are produced by a wide range of organisms, including archaea, bacteria, fungi, plants, and soil fauna. However, their complex composition and yet largely unknown abundance in environmental samples present significant challenges for their identification and quantification.

In this study, we cultured and collected EPSac samples from various organisms across a wide range of phyla belonging to archaea, bacteria, fungi, algae, higher plants, and soil fauna. The extraction methods were tailored to specific biological sample types, such as cation exchange resin extraction for microbial cells and water extraction for plant roots and soil fauna. Dissolved extracellular polysaccharides are purified from low molecular weight metabolites using ultrafiltration or precipitation prior to biochemical analysis. Plant samples will be cultivated hydroponically from seeds to minimize soil and microbial contamination of fine roots. To identify and quantify the monomeric composition of the polymers, we will employ an optimized acid hydrolysis method in combination with 1-phenyl-3-methyl-5-pyrazolone (PMP) derivatization, followed by analysis using ultra-high-performance liquid chromatography with high-resolution Orbitrap mass spectrometry (UPLC-Orbitrap MS).

EPSac-specific monomers will be seeked for that do not occur in other known cell wall-based and/or storage polysaccharides of prokaryotes and eukaryotes. To strengthen biological source attribution of EPSac, we will integrate their monomeric signatures with genomic information on EPS biosynthesis potential across representative taxa. By comparing detected monosaccharide profiles with lineage-specific biosynthetic capacities inferred from annotated EPS gene clusters, we aim to generate probabilistic links between chemical features and their likely biological origins. In parallel, machine-learning approaches such as random forest modeling, complemented by indicator species analysis, will be used to identify robust chemical and genomic biomarkers that distinguish EPSac produced by different organisms. These integrated biomarkers will then be applied to complex soil communities to infer the relative contributions of various taxes to soil EPS pools. Together, this chemical–genomic–computational framework provides a rigorous yet flexible strategy for tracing EPSac quantities and origins in soils and study their effect on soil physicochemical properties and soil biogeochemical processes.

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# Regulatory effects of Mortierella on soil microbial network stability and aggregate structure under saline-alkali stress

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**ABSTRACT**

Coastal regions face significant agricultural challenges due to soil salinization. Soil aggregates, serving as the fundamental architectural units of the soil matrix, are crucial for maintaining soil fertility, structural integrity, and ecosystem multifunctionality. Through field investigations and sampling within 20-30 km of the coastline, this study explores the complex interactions among microorganisms in saline-alkali soils and the mechanisms behind their synergistic remediation effects. Our results indicate that increasing soil salinity and exchangeable sodium percentage significantly reduced aggregate indices (mean weight diameter (MWD), R250) and soil organic carbon (SOC). Fungal α diversity decreased with salinity, whereas bacterial alpha diversity increased. Microbial communities structure diverged significantly under varying stress levels: bacterial and protistan communities were primarily driven by electrical conductivity (EC) and SOC, while fungal community structure was influenced by pH and soluble sodium. With intensifying stress, the ecological networks of both dominant and rare taxa became more complex, marked by significant increases in nodes, edges, network density, and average degree, alongside decreased modularity and the proportion of cross-domain connections. *Mortierella* was closely associated with SOC and aggregates. Its targeted removal, compared to random nodes removal, significantly reduced the proportion of cross-domain connections, an effect exacerbated by salinity, underscoring its key role in maintaining network stability. Furthermore, exogenous inoculation with a *Mortierella* consortium (*M. elongata*, *M. alpina*, and *M. capitata*) significantly increased soil extracellular polymeric substances (uronic acids and humic acids) and enhanced the MWD of aggregates in coastal saline soil. Our findings highlihgt that *Mortierella* is a key functional taxon regulating microbial network stability and aggregate structure, providing a promising microbial resource with both theoretical and practical implications for the bioremediation of coastal saline soils.

**Keywords:** Coastal saline soil; Soil aggregation; Microbial network; *Mortierella*; Soil organic carbon

# Functional Group Composition and Persistence of Extracellular Polymeric Substances in Soils

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**ABSTRACT**

Extracellular polymeric substances (EPS) constitute a significant component of soil organic matter (SOM) and play multifunctional roles in nutrient cycling, microbial survival, and soil health. However, the processes by which EPS are transformed and further retained by soil minerals remain poorly understood. This study investigated the chemical speciation of biogenic elements and mineral-SOM associations after EPS adsorption and turnover in typical clay minerals and three soils with varying mineral compositions, in order to distinguish the respective contributions of direct adsorption and microbial assimilation of EPS to SOM persistence. Synchrotron-based X-ray absorption near-edge structure (XANES) analysis revealed that incubation led to approximately twice as large changes in C and S speciation as EPS surface adsorption, suggesting stimulated microbial activity is a more important pathway for EPS to participate in SOM turnover. Incubation with EPS significantly increased carboxylic carbon by 10% while decreasing aromatics by 31% across the three studied soils. In-situ Fourier transform infrared (μ-FTIR) spectroscopy showed a 90% enhancement in Fe-organic associations (based on R2 increase) after incubation, whereas phyllosilicate-EPS associations were less stable and underwent disintegration in the Fe-rich, low-pH conditions of Mollisol and Alfisol. The differential preservation patters for various molecules arise from molecular fractionation, with carboxylic-rich compounds enriched on iron oxides and aromatic and aliphatic carbon enriched on phyllosilicates. Overall, EPS stabilizes SOM by stimulating the microbial carbon pump to assimilate native SOM and facilitating its association with iron oxides.

**Keywords:** EPS, Soil organic matter, Interfacial interaction, Mineral-organic composite

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# Modeling the Turnover and Stabilization of Soil Extracellular Polymeric Substances (EPS)

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**ABSTRACT**

Soil organic carbon (SOC) dynamics emerge from the interplay among plant inputs, microbial transformations, and mineral protection. Extracellular polymeric substances (EPS) have been proposed as an important pathway through which microbial carbon enters stabilized soil pools.

This study aims to develop and calibrate an isotope-informed process model that explicitly represents EPS、microbial biomass carbon (MBC) and microbial cellular necromass, in order to quantify the role of EPS in routing microbial-derived carbon into long-term stabilized organic matter.

The $^{13}C$ tracer incubation experiments were conducted in which pre-incubated soils received $^{13}C$-labeled EPS and $^{13}C$-labeled cellular necromass, followed by a 50-day incubation with measurements of $^{13}CO_2$ efflux, residual soil $^{13}C$-SOC, and total $^{13}C$ recovery. The model partitions each microbial-derived pool into fast-turnover and mineral-associated fractions and uses nonlinear kinetic formulations, including Michaelis–Menten uptake for microbial assimilation. Parameter estimation followed a three-step workflow: Sobol global sensitivity screening, nonlinear least-squares optimization to obtain optimal parameter set, and Markov chain Monte Carlo (MCMC) sampling to characterize parameter uncertainty.

The model captured the observed temporal patterns of $^{13}CO_2$ mineralization and soil $^{13}C$ retention with high fidelity (RMSE≈3.1% for predicted $^{13}$SOC). A rapid initial increase in $^{13}C$-labeled MBC was followed by stabilization as substrate availability declined. Approximately 39% of the cellular necromass pool and 19% of the EPS pool were assigned to fast-turnover fractions, indicating that most EPS persists in more stabilized forms, likely through mineral interactions or physical entrapment. Steady-state analysis further showed that EPS contributes to the mineral-associated organic matter pool and thus to long-term SOC stabilization.

Including EPS as a separate carbon pool in soil carbon models helps to better understand how microorganisms affect the stability of SOC and improves the ability to predict the formation of mineral-bound organic matter.

Currently, there are limited methods for extracting EPS, uncertainties in kinetic parameters, and only a few soil types are involved. All of these indicate the need to improve quantitative methods, validate models in more soils, and link parameters with soil properties to improve the applicability of models.

# Microbial extracellular residues dominate long-term soil organic carbon storage

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**ABSTRACT**

Soil microbes play a critical role in long-term soil organic carbon storage through processing of plant-derived carbon into less degradable forms and production of microbially-derived carbon during uptake of organic compounds, biosynthesis, growth and death. Although microbially-derived carbon includes both cellular and extracellular residues, and the mass of extracellular residues often exceeds microbial biomass, the contribution of cellular residues to soil carbon stocks is well established, while the role of extracellular residues is far less understood. Here we combine a continental-scale investigation with microcosm experiments and find that, contrary to prevailing concepts for soil carbon formation, microbial extracellular polymeric substances constitute the dominant soil microbial residue, and the primary source of microbially-derived carbon to the mineral associated organic carbon pool, which is less vulnerable to environmental disturbances. Our work provides new mechanistic insights into how soil microbiomes shape the fate of soil carbon and highlights the fundamental importance of microbial extracellular polymeric substances in controlling carbon sequestration under global change.

**Acknowledgments**

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# Investigating Microbial Intracellular and Extracellular Carbon Production Efficiency Using 13C and 18O Isotope Techniques

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**ABSTRACT**

Soil microbial carbon partitioning is a critical regulator of soil carbon cycling, yet how resource input systematically alters intracellular versus extracellular carbon allocation and efficiency remains unclear. Here, by integrating dual-isotope labeling ($^{18}O$-$H_2O$ and $^{13}C$-glucose) with microbial community analysis, we reveal a fundamental strategy shift in carbon metabolism. Glucose addition reversed the carbon allocation pattern: extracellular polymeric substance carbon ($C_{EPS}$) was 2.62-fold higher than growth carbon ($C_{growth}$) without amendment, whereas $C_{growth}$ exceeded $C_{EPS}$ with glucose. This re-allocation coincided with a marked decline in the production efficiency of both biomass and EPS. Mechanistically, glucose elevated the dominance of r-strategists from 58% to 71%, revealing a underlying mechanism: under low nutrients, K-strategists dominate, allocating more carbon to stable EPS, whereas high nutrient availability promotes r-strategists, shifting carbon toward growth and respiration and incurring an efficiency trade-off. Our study establishes a mechanistic framework linking environmental perturbation to carbon allocation by coupling community assembly with microbial physiology, providing crucial insights for predicting soil carbon dynamics under global change.

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# Mineral-EPS Interface Coupling Process: Contribution of Maillard Reaction-Driven Geological Polymerization to Carbon and Nitrogen Fixation

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**ABSTRACT**

Within the global carbon and nitrogen cycles, the transformation mechanisms of reactive carbon and nitrogen pools into stable pools constitute a central research topic in Earth sciences. Traditionally, this process has been regarded as primarily mediated by microorganisms, yet its conversion efficiency and stability are frequently constrained by environmental conditions. In recent years, abiotic transformation pathways—particularly the Maillard reaction (a condensation reaction between reducing sugars and amino acids widely observed in food chemistry)—have gained recognition for their potential to generate chemically stable, recalcitrant melanin-like polymers. These compounds are increasingly acknowledged as playing a crucial abiotic role in carbon and nitrogen sequestration within geological environments such as soils and sediments. Nevertheless, the mechanisms governing how this reaction is effectively driven under ambient natural conditions, including its key interfaces and catalytic pathways, remain poorly understood.

Consequently, this study proposes a core scientific hypothesis: the mineral-extracellular polymeric substance (EPS) composite interfaces, widely present in soils and sediments, constitute a natural pathway that drives efficient Maillard reactions, thereby promoting the geological polymerisation and long-term sequestration of carbon and nitrogen. EPS, as a naturally secreted microbial substrate reservoir, is rich in polysaccharides (reducing sugars) and proteins (amino acids) required for the Maillard reaction. Meanwhile, metal oxide minerals such as iron and manganese provide substantial specific surface area and abundant Lewis acid sites, serving a dual function of adsorbing and concentrating reaction substrates while catalysing key steps. Their coupling may substantially reduce the reaction energy barrier, enabling efficient carbon and nitrogen fixation under ambient temperature and pressure conditions.

To validate this hypothesis, this study designed a multi-scale experimental verification system. First, typical manganese ore (δ-$MnO_2$) and goethite (α-FeOOH) were selected as model mineral catalysts, with standard EPS extracted from activated sludge. A ‘mineral-EPS’ simulated reaction system was established and cultivated under controlled conditions of temperature (10–60°C), pH (7–8.5), and anaerobic conditions. The study comprehensively employed techniques including thermogravimetric-differential scanning calorimetry (TG-DSC), Fourier transform infrared spectroscopy (FTIR), ultraviolet-visible spectroscopy (UV-Vis), and near-edge X-ray absorption fine structure spectroscopy (NEXAFS) to systematically characterise the reaction processes and product properties. Key parameters monitored included the browning index, formation of C=N bonds, and generation of melanin-like polymeric compounds. To elucidate the transformation mechanism at the molecular level, high-resolution Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS) was employed to precisely analyse the evolution of molecular composition in soluble organic matter before and after the reaction.

The innovation of this study lies in its pioneering use of multi-technique corroboration to establish the mineral-EPS interface as a key site for efficient environmental Maillard reactions, revealing its catalytic polymerisation dynamics at the molecular scale. This not only positions classical abiotic chemical reactions within the core framework of geochemical cycles, offering a novel abiotic pathway explanation for understanding the global ‘missing carbon sink’ and formation of inert organic matter reservoirs, but also establishes a robust theoretical foundation for developing green, low-carbon technologies such as mineral-regulated soil carbon sequestration, sludge resource recovery, and marine carbon sequestration. Future research should quantify the absolute flux of this pathway within real environmental matrices and investigate the synergistic and competitive effects of different mineral types and microbial communities on interfacial processes.

# Pore-scale spatial heterogeneity of moisture and microbe interactions during moisture evaporation

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**ABSTRACT**

Soil aggregates are fundamental structural units that regulate microbial habitats and the fate of soil organic carbon. The spatial heterogeneity of water and oxygen at the pore scale within aggregates directly influences microbial metabolic activities, thereby determining whether organic carbon is rapidly decomposed or stabilized over the long term. However, due to the high heterogeneity and complexity of soil structure, these microscale processes have long been challenging to quantify and resolve directly. Here, we combined millimeter-scale microfluidic chips simulating soil aggregate pore networks, confocal laser scanning microscopy, and time-of-flight secondary ion mass spectrometry to simultaneously visualize pore water distribution, microbial biomass, extracellular polymeric substances (EPS), and key molecular features of microbial metabolism. Our results show that under conditions of water evaporation, radial water gradients and spatial differentiation of microbial survival gradually form within aggregates. Due to higher oxygen accessibility in the outer pores, microbial activity is elevated, leading to increased microbial biomass and EPS secretion in the outer layer, which enhances water retention and slows water loss during evaporation. In contrast, internal pores experience oxygen limitation, suppressing microbial growth; during evaporation, internal regions lose water preferentially, and microbes transition from oxygen limitation to water stress, maintaining low metabolic activity over time. At the molecular level, these spatial differentiations are further explained by biological mechanisms. Microbial communities in the outer pores exhibit growth-oriented resource allocation, characterized by enhanced protein and phospholipid signals and EPS enriched in protein components, indicative of high metabolic activity and rapid organic matter turnover. In contrast, microbes in the internal pores allocate more resources toward defense and environmental maintenance, as shown by EPS rich in polysaccharides, reduced metabolic activity, and localized accumulation of microbial residues. The coexistence of these different survival strategies within aggregates reveals, at the molecular scale, how pore-scale water and oxygen gradients drive functional partitioning of microbial communities. Overall, this study reveals the pore-scale interactions between water and microbes and their effects on spatial heterogeneity in organic carbon turnover. These findings provide mechanistic insights into aggregate-scale carbon stabilization and turnover and offer theoretical and technical support for understanding the dynamic regulation of soil water and carbon fluxes under changing climatic conditions.

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# Plant growth-promotion triggered by poly-γ-glutamic acid is associated with facilitation of bacterial cross-feeding networks of the rhizosphere

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**ABSTRACT**

Despite the critical role rhizosphere microbiomes play in plant growth, manipulating microbial communities for improved plant productivity remains challenging. One reason for this is the lack of knowledge on how complex substrates secreted in the microbiome ultimately shape the microbe-microbe and plant-microbe interaction in relation to plant growth. One such complex substrate is poly-γ-glutamic acid, which is a microbially derived extracellular polymer. While it has previously been linked with plant growth-promotion, the underlying mechanisms are not well understood. Here we show that this compound benefits plants by fostering cross-feeding networks between rhizosphere bacteria. We first experimentally demonstrate that poly-γ-glutamic acid application increases potassium bioavailability for tomato plants by driving a shift in the rhizosphere bacterial community composition. Specifically, application of poly-γ-glutamic acid increased the relative abundance of *Pseudomonas nitroreducens* L16 and *P. monteilii* L20 bacteria which both promoted tomato potassium assimilation by secreting potassium-solubilizing pyruvic acid and potassium-chelating siderophores, respectively. Although either *Pseudomonas* strain could not metabolize poly-γ-glutamic acid directly, the application of poly-γ-glutamic acid promoted the growth of *Bacillus* species, which in turn produced metabolites that could promote the growth of both *P. nitroreducens* L16 and *P. monteilii* L20. Moreover, the *P. monteilii* L20 produced 3-hydroxycapric acid, which could promote the growth of *P. nitroreducens* L16, resulting in commensal cross-feeding interaction between plant growth-promoting bacteria. Together, these results show that poly-γ-glutamic acid plays a crucial role in driving plant growth-promotion via bacterial cross-feeding networks, highlighting the opportunity for using microbially derived, complex substrates as catalysts to increase agricultural productivity.

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# Nitrogen deposition reorganizes extracellular polymeric substances production through microbial physiological adjustments in subtropical forest soils

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## ABSTRACT

Root–microbe interactions strongly influence the production of microbial extracellular polymeric substances (EPS), a key intermediate linking microbial metabolism to soil organic carbon (SOC) stabilization. However, how nitrogen (N) deposition regulates EPS production in soils with and without root influence remains unclear. Here, we applied long-term N addition (0, 40, 80 kg $N \cdot ha^{-1} \cdot yr^{-1}$) combined with root exclusion in a subtropical *Castanopsis carlesii* natural forest to assessed how N enrichment and roots presence jointly affect microbial EPS production, production efficiency, and contribution to SOC. Nitrogen addition showed a nonlinear response, reducing EPS concentrations by 20–26%, mainly through declines in microbial biomass carbon (MBC) and carbon use efficiency (CUE), which together constrained carbon available for extracellular synthesis. In contrast, EPS production efficiency increased by up to 40%, and was accompanied by elevated carbon- and phosphorus-acquiring enzyme activities, indicating enhanced metabolic allocation under nutrient imbalance. Although EPS-derived carbon (EPS-C) accounted for only 0.3%–0.5% of SOC, its proportion increased significantly under nitrogen addition, particularly in root-free soils. This finding suggests that EPS may serve as an important microbial carbon pool under conditions of limited plant input or weakened root activity. These results demonstrate that long-term N deposition reorganizes microbial carbon allocation and extracellular stabilization pathways through coordinated shifts in MBC, CUE, and enzyme stoichiometry in subtropical forest soils.

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# Mechanisms of simulated warming and altered precipitation on microbial metabolism residues in soils of abandoned land

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## ABSTRACT

Cropland abandonment is an important ecological restoration practice on the Loess Plateau, enhancing soil quality and regional carbon (C) sequestration. Microbial metabolic residues, including microbial necromass (MNC) and extracellular polymeric substances (EPS), represent major contributors to soil organic carbon (SOC) pools. However, how climate change regulates microbial residue accumulation and its contribution to SOC in abandoned cropland remains unclear. Here, we investigated a 12-year abandoned cropland ecosystem in the loess hilly region using an in situ climate-manipulation experiment that simulated warming (~1.42 °C) and five precipitation gradients. Biomarker-based microbial residue analysis and microbiome approaches were combined to clarify the responses and underlying mechanisms. (1) Increased precipitation, rather than warming, significantly enhanced topsoil SOC pools and their relative proportions, with SOC increasing by an average of 1.91% for every 10% increase in precipitation. Warming mainly increased microbial biomass C but had no significant effect on SOC pools, and its interaction with precipitation showed antagonistic effects. Mineral-associated organic matter (MAOM) contained approximately twice as much carbon as particulate organic matter (POM) (3.84 vs. 1.95 g $kg^{-1}$) and exhibited greater chemical recalcitrance. However, increasing precipitation reduced MAOM recalcitrance, likely due to enhanced fresh C inputs and weakened mineral protection under higher soil moisture. (2) Both MNC and EPS contents increased with rising precipitation gradients, while warming promoted only the accumulation of EPS uronic acids. Fungal necromass dominated MNC, with contents approximately six times higher than bacterial necromass. EPS was mainly composed of polysaccharides (63.12%), followed by proteins (26.59%) and glyoxylates (10.29%). The accumulation coefficients of MNC and EPS were 13.93 and 2.12, contributing 31.45% and 4.75% to SOC, respectively. Although MNC showed a much higher accumulation coefficient and C contribution than EPS, increasing precipitation significantly reduced the relative contribution of MNC while enhancing that of EPS, indicating that improved moisture conditions favor EPS-mediated C sequestration. SOC fractions and microbial residue contents increased over time following abandonment, highlighting the positive effects of restoration on soil C accumulation. (3) Microbial community responses showed that warming reduced bacterial diversity and network complexity, whereas increasing precipitation enhanced both, with warming offsetting precipitation-driven gains. Increased precipitation alleviated microbial nitrogen limitation and competitive pressure, and promoted biomass production (Y-strategy) and resource acquisition (A-strategy), while reducing stress-tolerance (S-strategy). Microbial community assembly processes were strongly linked to diversity patterns, indicating climate-driven shifts in microbial assembly mechanisms. (4) Driving mechanisms differed markedly between MNC and EPS. While both were positively correlated with plant biomass, soil moisture, substrate availability, and mineral protection, microbial community properties explained only a small fraction of MNC variation (≤3%), but accounted for most of the EPS variation (>50%). Structural equation modeling revealed that MNC accumulation was primarily driven by substrate availability, whereas EPS accumulation was jointly regulated by soil environment, substrate supply, mineral protection, and microbial traits. Notably, EPS enhanced both POM- and MAOM-C, resulting in a stronger direct effect on SOC than MNC.Overall, this study highlights precipitation as a dominant regulator of microbial residue-derived carbon sequestration in abandoned cropland on the Loess Plateau and provides mechanistic insights for predicting regional carbon sinks under future climate scenarios.

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# Microbial Legacy: The Differential Transformation of Biomass Components into Soil Organic Matter

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## ABSTRACT

Microbial cell and extracellular polymeric substances (EPSs) are recognized as critical precursors of soil organic carbon (SOC), yet their differential stabilization mechanisms remain poorly understood. To elucidate the micro-mechanisms governing the transformation of these "microbial legacy" into SOM, we conducted a 112-day incubation experiment using soil amended with $^{13}$C-labeled bacterial and fungal biomass components (intact cells, extracellular polysaccharides[EPSc], and extracellular proteins [EPSp]) . We tracked C partitioning into $CO_2$, diverse SOM fractions (physical and chemical), and the change of microbial necromass carbon (MNC) to compare their stabilization pathways.

Results indicated that substrate origin and chemical composition distinctively regulated carbon fate. Fungal-derived components exhibited superior persistence with >81% SOC recovery, while bacterial EPSp showed the highest mineralization (21.3%). Notably, bacterial components induced persistent negative priming effects, effectively suppressing native SOC decomposition, whereas fungal EPSp triggered positive priming despite low self-mineralization. EPSc preferentially stabilized through mineral association (MAOC), with F-EPSc uniquely achieving sustained MAOC accumulation. EPSp predominantly contributed to humic acid formation, particularly F-EPSp (39% recovery in HA-C). Cell components promoted MNC accumulation, while EPSc addition dramatically depleted bacterial necromass, shifting communities toward fungal dominance. Microbial community analysis identified *Bacillus* (bacteria) as the primary driver of rapid mineralization, while *Mortierella* (fungi) was crucial for carbon assimilation and stabilization. Partial least squares path modeling (PLS−PM) demonstrated thatfungal diversity was the strongest positive driver of SOC accumulation (r=0.836) through mineralization suppression, while bacterial diversity accelerated carbon loss.

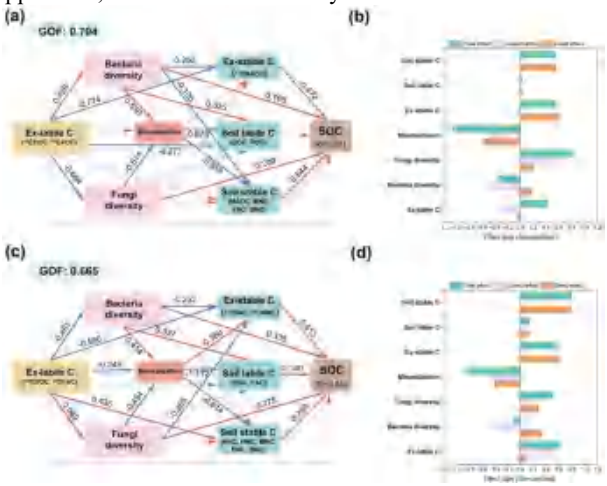



**Figure 1.** PLS−PM analysis of the effects of DOC, bacterial and fungal microbial communities, mineralization, MAOC, POC, FA-C, HA-C, HM-C, and microbial necromass carbon (MNC, FNC, BNC) on SOC. The models are based on two different soil organic matter fractionation schemes: (a, b) physical density fractionation and (c, d) chemical humus fractionation.

These findings demonstrate that fungal cells and EPSc serve as superior precursors for stable SOM, while bacterial proteins favour rapid turnover. This study provides process-level evidence for the SOM transformation, demonstrating that microbial biomass components undergo different transformation pathways, linking biomass chemistry to distinct SOM formation pathways within both continuum and humus frameworks, and highlighting the trade-off between bacterial-driven mineralization and fungal-mediated SOC sequestration.

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# Effect of Humic acid on lysozyme interaction with montmorillonite and kaolinite

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## ABSTRACT

Humic acid (HA) as a soil organic matter (NOM) can participate in the interaction between proteins and clay minerals, depending on clay type, HA and protein content, and solution conditions. The effect of HA on the interaction of lysozyme (LSZ) with kaolinite (Kao) and montmorillonite (Mont) was investigated at (initial) $pH_i$ 5 and 8. LSZ adsorption on clays in the presence of HA is dominated by adsorption of HA/LSZ complexes. The HA/LSZ mass ratio ($f_{IEP,pH}$) at the iso-electric point (IEP) is pH dependent. At $f < f_{IEP,pH}$ the HA/LSZ complexes are positively charged and adsorb well to the negatively charged Mont and Kao surface fractions. The adsorption levels on Mont are considerably larger than on Kao, which is mainly due to the much larger area fraction of modestly hydrophobic basal plates of Mont. The presence of HA increased the plateau adsorption of LSZ on Kao and Mont for both $pH_i$ values, and the LSZ adsorption increased with increasing HA content and $pH_i$ values. At $pH_i$ 8 complications arised for low initial LSZ concentrations, for $f < f_{IEP,pH}$ the HA/LSZ complexes were only weakly positive and formed dispersed aggregates and for $f > f_{IEP,pH}$ the HA/LSZ complexes were negative, both conditions caused relatively high equilibrium concentrations of LSZ in solution that decreased with increasing initial LSZ concentration. The present results enhance our insight in protein soil interactions for the case that clay particles are brought in contact with aqueous solutions that contain modest amounts of both NOM and protein and stress the importance of the NOM/protein mass ratio and solution pH.

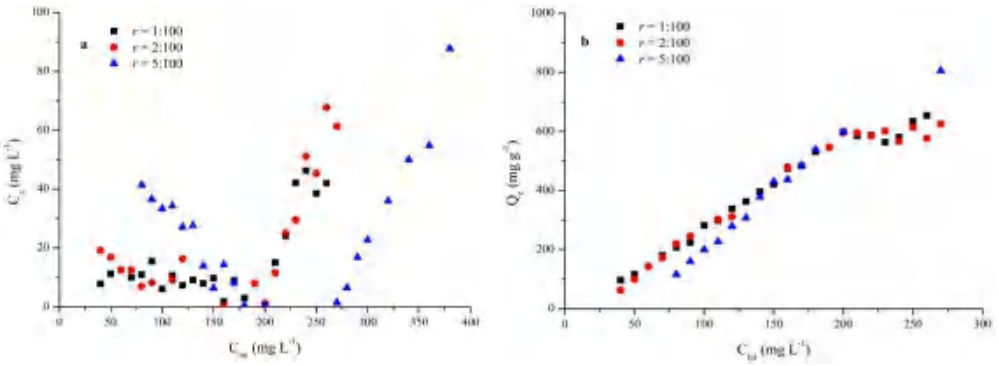



Figure 1. LSZ adsorption on montmorillonite at at $pH_i$ 8 with different HA/clay mass ratios *r*.

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# Biochar effects on soil physicochemical properties and biological activity in Mediterranean agricultural soils

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**ABSTRACT**

Intensive agriculture degrades soil health, while the recovery of abandoned soils may take decades. Sustainable soil management requires strategies that improve soil physicochemical conditions while supporting soil biological functioning. In this sense, biochar, produced through the pyrolysis of organic waste, has emerged as a promising amendment to improve soil physicochemical properties and stimulate soil biological processes, although its effects depend strongly on soil characteristics and management history.

In this study, three contrasting agricultural soils from southern Spain (olive grove, avocado plantation and abandoned cereal field) were amended with biochar (produced by *FENIX* project; pyrolyzed at 500 °C for 15 min) at rates of 2.5% and 5% (v/v) and incubated for three months alongside untreated controls. Soil physicochemical and biological properties (CEC, pH, nutrients, enzymatic activities, microbial biomass, respiration, and fungal and prokaryotic rhizospheric community composition) were evaluated, and a greenhouse pot experiment with lettuce (three consecutive one-month cultivation cycles) was conducted to assess plant responses.

Results pointed out that soil type and management history were the primary drivers of variability among samples. When analysed individually, biochar amendments induced substantial changes in several soil properties after the incubation period. In the olive and abandoned cereal soils, biochar application increased the availability of exchangeable $K^+$, likely reflecting the high K content of the biochar. In contrast, soluble $Mg^{2+}$ and $Ca^{2+}$ decreased in the avocado soil, possibly due to adsorption processes. In the abandoned cereal soil, urease activity increased with biochar addition, suggesting enhanced microbial activity linked to increased carbon inputs. Biochar amendments also reduced the solubility or availability of several micronutrients (Zn, Cu, B) and decreased bioavailable Mn and available P. Increasing biochar application rates drove measurable shifts in microbial community composition and interconnectivity, indicative of altered nutrient cycling and carbon dynamics. Despite these changes in soil properties and biological activity, no significant effects on lettuce growth were observed, possibly due to the short experimental duration, the rapid crop cycle, and the absence of strong nutrient limitations.

These results highlight the strong soil-specific responses of biochar amendments and underscore the importance of considering soil type when evaluating biochar as a strategy to enhance soil health and biological functioning in Mediterranean agroecosystems.

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# Evaluating tillage effects on soil biodiversity across functional groups using extracellular eDNA

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**ABSTRACT**

Soil biota drive many essential soil functions that underpin ecosystem services in agriculture. Assessing soil biodiversity is therefore crucial for understanding the effects of management practices, such as tillage, on biological soil health. Molecular techniques including DNA metabarcoding are widely used to study soil biodiversity and have proven effective for microbial soil organisms. To extend their potential to soil fauna, methodological adaptations are needed, particularly to accommodate the larger body sizes and different environmental DNA (eDNA) distribution patterns associated with faunal organisms. In this study we analyzed extracellular eDNA (exDNA) extracted from larger volumes of soil to enable the simultaneous assessment of multiple soil microbial and faunal taxa. Employing an integrated metagenomic and metabarcoding approach, we applied this exDNA method to assess the functional diversity of belowground communities in arable soils of Austria subjected to different tillage intensities. Faunal taxa were assigned to functional categories based on traits linked to their trophic roles and ecological strategies, which could be used to derive bioindicators for assessing soil health. Similarly, microbial analysis targeted key functional groups, and genes associated with vital soil functions. Such comprehensive assessments of soil functional diversity using exDNA may advance integrative soil health diagnostics to thoroughly evaluate the impacts of agricultural management practices.

# Long-Term Effects of Nitrogen and Lime Application on Plant–Microbial Interactions and Soil Carbon Stability in a Semi-Arid Grassland

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**ABSTRACT**

This study investigated the long-term (70 years) effects of N fertilisation (ammonium nitrate [AN], ammonium sulphate [AS]) at 70 and 211 kg N kg/ha, and liming (L) on plant–microbial interaction and soil carbon stability in a semi-arid grassland in South Africa. Aboveground biomass increased with N addition, particularly AN211, showing a 119% increase compared to the control, while both liming and N applications increased belowground biomass. Nitrogen addition significantly altered plant stoichiometric ratios, with root N ratios showing greater treatment-induced variation (12.7–51.3) than shoot N ratios (10.2–16.8). Microbial biomass carbon peaked with AN70 treatment, while dehydrogenase activity was highest in lime-only plots but suppressed in non-limed N treatments. Conversely, urease activity was highest in the control group and suppressed in most fertilised treatments. Despite increased biomass production, SOC remained unchanged across treatments (49.7–57.6 g/kg), whereas soil pH was lowest (<3.5) and highest (>6) under N fertilisation and lime, respectively. PCA revealed distinct clustering of treatments, with N forms differentially affecting plant allocation patterns and microbial parameters. This study demonstrates that plant–soil–microbe stoichiometric imbalances and pH-induced limitations on microbial function explain the disconnect between plant productivity and carbon sequestration in this semi-arid grassland ecosystem.

**Acknowledgments**

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# Linking Soil Food Web Stoichiometry to Ecosystem Function and Soil Health

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**ABSTRACT**

Ecological stoichiometry serves as a fundamental mechanism governing nutrient cycling in ecosystems. Organic substitution changes soil carbon, nitrogen, and phosphorus balance by introducing exogenous organic materials with distinct stoichiometric profiles, thereby compelling soil biota to adapt through multifaceted strategies. However, systematic understanding of how the soil food web responds to such stoichiometric imbalance remains elusive. To address this knowledge gap, we examined the response of soil food web community composition and multi-trophic network structure to elemental stoichiometric shifts in agricultural ecosystems. Organic substitution consistently increased the relative abundance of K-strategist bacteria, consumer protists, and bacterivorous nematodes, while reducing parasitic protists and plant-parasitic nematodes. Arthropod communities, particularly *Mesostigmata* and *Cryptostigmata* mites, exhibited pronounced responses. These shifts were strongly correlated with soil nutrient limitation and stoichiometric imbalances. Furthermore, organic substitution reconfigured the elemental stoichiometric network of the "crop-soil-biota" continuum by modulating nutrient availability and biological processes. Our findings elucidate the mechanisms underlying multi-trophic reorganization within soil food webs and demonstrate how stoichiometric coupling mediates ecosystem responses to resource inputs. This work advances ecological stoichiometry theory in soil ecology and provides a theoretical framework for optimizing agricultural nutrient cycling through the lens of "resource input–biological response–functional output" dynamics.

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# Enzyme-Mediated Nutrient Dynamics in Cover Crop Systems: Temporal and Spatial Optimization Strategies

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## ABSTRACT

Enzyme activities serve as critical indicators of soil biological function and nutrient cycling, yet their temporal dynamics and spatial distribution following cover crop incorporation are not well understood in degraded sandy soils. This study investigated how monoculture versus mixed cover cropping systems influence the temporal and depth-dependent patterns of key hydrolytic enzymes mediating carbon, nitrogen (N), and phosphorus (P) cycling in Myakka sandy soils of subtropical Florida. Six treatments were established at the Gulf Coast Research and Education Center, Wimauma, FL in May 2024: sorghum-sudangrass (SS) 33.63 kg ha$^{-1}$, sunn hemp (SH) 56.04 kg ha$^{-1}$, southern pea (SP) 56.04 kg ha$^{-1}$, SH + SP (28.02 + 28.02 kg ha$^{-1}$), SH + SS (28.02 + 16.81 kg ha$^{-1}$), and weedy fallow (WF) control using a randomized complete block design with three replications. Baseline conditions revealed characteristic limitations of degraded sandy soils: low soil organic matter (1.66% surface, 1.14% subsurface), acidic pH (5.27 surface), and stratified P availability (311.5→181.5 mg kg$^{-1}$ with depth). Following 80-day growth periods, cover crop biomass was incorporated and soil enzyme activities (β-glucosidase, N-acetyl-β-D-glucosaminidase, and acid phosphatase) were quantified colorimetrically at 0–15 and 15–30 cm soil depths across 2, 4, and 6 weeks post-incorporation. Mixed-model analysis of variance (ANOVA) revealed pronounced temporal dynamics ($p<0.001$), depth stratification (P<0.001), and enzyme-specific responses (P<0.001), with significant treatment × enzyme ($p<0.001$) and treatment × week× enzyme ($p=0.005$) interactions. All enzymes exhibited synchronized peak activities at week 4 post-incorporation, and declined thereafter, while surface horizons maintained 50–100% greater activities than subsurface layers. Although main treatment effects were statistically non-significant ($p=0.199$), the SH+SS legume-grass mixture consistently demonstrated superior enzyme activities, particularly for acid phosphatase and N-acetyl-β-D-glucosaminidase, suggesting enhanced microbial processing of organic P and N substrates. These results showed a critical 4-week temporal window post-incorporation where enzyme-mediated nutrient release is maximized, providing actionable guidance for optimizing subsequent crop planting schedules to synchronize nutrient availability with crop demand while minimizing leaching losses in vulnerable sandy soils. The superiority of legume-grass mixtures indicates that functional diversity in cover crop systems enhances enzyme-mediated biogeochemical cycling, offering an innovative approach to improving nutrient retention in chemically and biologically degraded subtropical agroecosystems.

**Keywords:** Soil enzyme activities, Cover crop mixtures, Nutrient cycling, Sandy soils

**Acknowledgments**

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# Steering soil microbiomes for healthier crops

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**ABSTRACT**

A healthy soil microbiome is important for plant growth. This is certainly true in agricultural systems, and is now acknowledged broadly. I will present results from our recent work showing how the composition and diversity of soil microbial communities influence the growth and, more importantly, also the health and nutritional quality of crops. An important question is how to change these soil microbial communities to improve crop growth and health. I will discuss the transient nature of soil microbiomes and how we can use plants to steer the composition of soil microbiomes. I will show how specific the effects are of plants on the soil microbiome, but also how sensitive plants are to changes in the soil microbiome. I will also show how neighboring plants influence the root associated microbiome of a focal crop and the consequences of the neighbor effects on the microbial community for plant growth and yield. By understanding how different crops influence desired groups of soil microorganisms and the temporal dynamics of these effects we can design combinations of crops, in rotation or intercropping systems that improve the performance of a focal crop.

# Rewiring Micro-Food Webs: How Copper Nanopesticides Can Reshape Nitrogen Fluxes via Trophic Decoupling

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**ABSTRACT**

The extensive application of copper-based nanopesticides (Cu-based NPs) in agroecosystems can pose significant ecological risks to soil nitrogen (N) cycling through microbial-mediated mechanisms, yet food web-driven regulatory feedbacks remain poorly understood. Through a microcosm experiment with CuO nanoparticles (CuO NPs) and silica-encapsulated CuO@$SiO_2$ NPs (applied at 20 and 200 mg/kg), we demonstrate how micro-food web interactions (bacteria, fungi, protists, nematodes) govern N transformation dynamics. Integrated enzymatic and ecological network analyses revealed that both NPs reduced microbial biomass nitrogen (MBN) and bioavailable N species. Critically, high-dose CuO@$SiO_2$ (200 mg/kg) strongly inhibited nitrite reductase (NiR, 44.8%), creating a denitrification bottleneck. Elevated β-1,4-glucosidase: β-1,4-N-acetyl-glucosaminidase (BG: NAG) ratios indicated decoupled carbon-nitrogen cycling, favoring oligotrophic bacteria (e.g., *Sphingomonas*) over sensitive fungi (*Olpidiomycota*). NPs disproportionately impacted high-trophic-level microfauna, restructuring micro-food web topology. Network modeling uncovered concentration-specific trophic cascades: CuO@$SiO_2$ intensified protistan predation, disrupting nematode-microbe linkages and weakening top-down control of nitrifiers/denitrifiers. This triggered 71.8% higher $N_2O$ emissions while reducing soil N supply capacity by 36.1% at high-dose NP exposure. Conversely, low-dose CuO NPs maintained N turnover through reinforced bacterial-protist-fungal connectivity. Crucially, NP impacts exhibited non-linear, threshold-mediated dynamics: low concentrations induced metabolic adaptations (enzymatic stoichiometry shifts), while high doses caused functional collapse (denitrification inhibition). Our findings establish that micro-food web restructuring—not merely microbial toxicity—determines NP effects on biogeochemical cycles. This underscores the imperative to incorporate trophic interactions into nanomaterial risk assessments for accurate prediction of agroecosystem functions.

**Keywords:** Nanopesticide; multi-trophic interaction; micro-food web; nitrogen cycling; ecotoxicology

# Contrasting global patterns and drivers of soil bacterial and fungal diversity responses to crop rotation

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**ABSTRACT**

Crop rotation is widely implemented to enhance agricultural sustainability, with its benefits for soil health and crop productivity closely linked to changes in the soil microbiome. However, the global-scale effects of crop rotation on soil microbial communities remain poorly understood. Here, we conducted a global meta-analysis combining 2177 paired observations, based solely on high-throughput sequencing data, to evaluate how crop rotation influences bacterial and fungal diversity, community structure, and their relationships with crop yield and environmental factors. We found that crop rotation significantly increased bacterial alpha diversities (Shannon diversity and species richness) but not beta diversity. In contrast, crop rotation significantly increased fungal beta diversity but not alpha diversity. Crop rotation altered both bacterial and fungal community structure. Moreover, transitioning from legume to non-legume crops in crop rotations induces greater changes in bacterial Shannon diversity and fungal beta diversity, as well as in both bacterial and fungal community structure, than the reverse transition. Bacterial Shannon and fungal beta diversities increase with rotation duration and the number of rotational cycles. Random forest models revealed that microbial responses to crop rotation are modulated by mean annual temperature, but not by soil physicochemical properties. Moreover, soil texture influenced the response ratio of fungal richness, with significant decreases in fine-textured soils. The response ratios of bacterial and fungal alpha diversity were positively correlated with the response ratios of crop yield and soil chemical properties (e.g., pH, soil organic carbon, available nutrients), while the response ratios of beta diversity and community structure were not. Our findings demonstrate that bacterial and fungal communities respond differently to crop rotation, and that increases in microbial alpha diversity under rotation mediate improvements in soil health and crop productivity. Future research should focus on microbial functional responses and crop type transitions under diverse agroecosystems to better integrate soil microbiomes into sustainable agricultural systems and maximize the benefits of crop rotation.

# The effect of iron-bound organic carbon on fungal denitrification in regulating upland red soils $N_2O$ emission

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**ABSTRACT**

Agricultural soil serves as a significant source of anthropogenic $N_2O$ emissions. Compared to bacteria, the role of fungi in $N_2O$ emissions from upland soil cannot be ignored. Our previous research has shown that fungi contributed approximately 60.11% of $N_2O$ emissions in acidic red soil of upland. Notably, acidic red soil is characterized by a high content of iron elements, which readily combine with soil organic carbon to form iron-bound organic carbon (Fe-OC). Besides, our study showed that a positive correlation between Fe-OC and fungal denitrification potential. However, the mechanism by which iron-bound organic carbon affects fungal denitrification on $N_2O$ emission in upland red soil is still unclear, especially under the addition of exogenous organic matter. Our study aims to investigate dynamic changes in iron oxide forms, their concentrations, and associated organic carbon (Fe-OC) in upland acidic red soil with long-term addition of exogenous organic matter through field in situ experiments. Furthermore, our examined the impact of $^{15}N$-labeled Fe-OC on soil $N_2O$ emissions-based laboratory cultivation experiments. Our findings of this research can provide an important theoretical basis for the mechanism of denitrifying fungi affected by iron-bound organic carbon in aridic red soil impacting agricultural $N_2O$ emissions.

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# Unraveling soil microbial guilds driving phosphorus, nitrogen, and carbon transformations through multi-omics approaches

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**ABSTRACT**

Our studies provide new insights into the ecological and functional complexity of soil microbial communities and their central role in regulating the biogeochemical cycles of phosphorus (P), nitrogen (N), and carbon (C) in agricultural and semi-natural soils. Using an integrative multi-omics framework—including metagenomics, metaproteomics, metatranscriptomics, and metagenome-assembled genomes (MAGs)—we characterized the taxonomic composition, functional specialization, and environmental responses of soil microbiomes under varying fertilization practices, crop phenology, and organic matter dynamics. We identified highly specialized microbial guilds that drive key transformations within the P, N, and C cycles. In the P cycle, a functional division was observed between microorganisms responsible for the solubilization of inorganic P and those involved in the mineralization of organic P. Actinobacteria were predominant carriers of solubilization genes, while other bacterial and archaeal groups specialized in organic P mineralization, revealing evolutionary adaptations to distinct nutrient sources. Archaea, historically underestimated in P cycling, were found to encode multiple P-metabolism genes, indicating complementary or even essential roles alongside bacteria. Metaproteomic data highlighted the alkaline phosphatase PhoX as a potential biomarker of P bioavailability. In the nitrogen cycle, our results demonstrate that microbial functional niches are sharply defined and largely governed by crop phenology, which modulates the abundance and activity of nitrification and denitrification genes more strongly than fertilization. Distinct guilds of nitrifiers (e.g., Nitrososphaeraceae) and denitrifiers (e.g., Propionibacteriaceae) were identified, each with discrete metabolic roles. These findings indicate that synchronizing fertilization schedules with phenological stages of high microbial activity can improve nutrient use efficiency and mitigate environmental losses. Regarding the carbon cycle, our analyses challenge the traditional paradigm that fungi dominate the decomposition of complex organic matter. We identified diverse bacterial decomposer guilds—including Chitinophaga, Pedobacter, Terriglobus, and Asticcacaulis—specialized in degrading chitin, β-1,3-glucans, and cellulose. Metatranscriptomic evidence showed that bacterial decomposers often exhibited higher metabolic activity than fungi, underscoring their crucial role in organic matter turnover and carbon sequestration. Together, these findings highlight the strong influence of plant phenology on microbial functionality and reveal the need to align nutrient management with the dynamic activity of soil microorganisms. The integration of multi-omics data also enabled the identification of functional biomarkers with potential for predictive applications in soil health assessment. By coupling molecular data with machine learning, we provide a framework to anticipate soil microbiome responses to management or climatic change. Overall, this research advances the mechanistic understanding of soil microbial ecology and supports the development of microbiome-informed strategies for sustainable nutrient management, soil fertility enhancement, and climate-smart agriculture.

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# Multi-scale Biochar-hydrogel for Enhanced Soil Health and Crop Production

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**ABSTRACT**

Soil degradation, nutrient loss, and declining water-use efficiency are major challenges threatening agricultural productivity and sustainability under changing climate conditions. Conventional fertilizers and soil amendments often fail to maintain nutrient availability and microbial viability over time, leading to inefficient nutrient use and increased environmental losses. Biochar (BC) and hydrogels (HG) have individually shown promise for improving soil fertility and water retention; however, their performance remains inconsistent due to differences in material properties, soil types, and management conditions. This research develops and tests innovative soil amendments made from multi-scale biochar–hydrogel (BC–HG) nanocomposites that incorporate nano-biochar (NBC) to improve soil health and crop productivity. These materials are designed to enhance soil structure, regulate water retention and release, increase nutrient sorption, and support beneficial soil microbes under stress conditions such as drought or nutrient limitation. Despite their potential, the optimal material composition and mechanisms by which these composites affect soil processes and plant–microbe interactions are not well understood, and field-scale evidence remains limited. To address these gaps, the research integrates materials engineering, soil biogeochemistry, and plant-microbe ecology to (1) develop and characterize BC–HG nanocomposites for improved microbial encapsulation and delivery, (2) evaluate their effects on nutrient cycling, microbial activity, and plant growth under controlled drought and reduced fertilizer inputs, and (3) validate their performance and environmental impacts in contrasting field soils. The outcomes will provide new insights into how nanocomposite design influences soil function and crop productivity, advancing practical, sustainable technologies for enhancing nutrient-use efficiency, soil resilience, and agricultural sustainability under changing climate conditions.

**Keywords:** Biochar, Nanotechnology, Hydrogel, Biofertilizer, Soil, Plant

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# Interactive Effects of Compost, Clay, and Plant Presence on Soil Aggregate Fractions and Biochemical Properties in Sandy Soil

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**ABSTRACT**

Improving sandy soil structure and fertility requires a combined approach integrating organic and mineral amendments under plant influence. This study investigated the impact of compost, clay, and their combination, with or without plant presence, on the distribution of soil fractions and biochemical properties. A glasshouse experiment was conducted using Kikuyu grass (*Pennisetum clandestinum*) grown in sandy soil amended with compost (2–4% w/w), bentonite clay (2% w/w), or their combinations. After 12 weeks, soils were fractionated into macro (>2 mm), meso (0.25–2 mm), and micro (<0.25 mm) fractions, and analysed for microbial biomass carbon (MBC), pH, EC, $NH_4^+$, $NO_3^-$, and cation exchange capacity (CEC). A significant interaction between treatment and plant presence occurred for macro- and meso-fractions, indicating that plant roots modified the effects of amendments on structural dynamics. Compost, alone or combined with clay, promoted macro-fraction formation and enhanced MBC, whereas clay primarily contributed to improvements in pH and CEC. The presence of plants amplified MBC and $NH_4^+$ but decreased $NO_3^-$ and EC, suggesting enhanced microbial activity and nutrient uptake within the rhizosphere. Overall, compost acted as the main driver of structural and biological improvement, while clay provided chemical buffering and stabilization. The combined application maintained structure under plant influence, highlighting the complementary roles of organic–mineral interactions in improving sandy soil function.

**Keywords:** Clay, Compost, Soil fraction, Plant growth, Sandy soils

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# Synergistic Effects of Clay, Hay residue, and Fertilizer in Sandy Soil

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**ABSTRACT**

Sandy soils are inherently low in physical, chemical, and biological fertility, limiting their capacity to retain nutrients and organic matter. A glasshouse experiment was conducted to examine the effects of kaolinite clay (0 and 5%), hay residue as an organic amendment (0 and 4%), and nitrogen–phosphorus–sulphur (NPS) fertilizer on the physical and biological properties of a sandy soil. Soils were sampled after 2, 12, and 20 weeks to assess changes in soil fraction distribution (micro <0.25 mm, meso 0.25–2.0 mm, and macro >2.0 mm), microbial biomass, nutrients, and microbial community structure. A two-way ANOVA revealed that harvest time, treatment, and their interaction significantly affected all measured parameters. Treatments combining clay with hay residue, with or without fertilizer, significantly increased macro-fraction formation by approximately 2–4 times compared to the control ($p < 0.001$), indicating improved soil structure and aggregate stabilization over time. Microbial biomass carbon and nitrogen were also higher in these treatments ($p < 0.05$), whereas fertilizer alone or with clay had limited effects. Fungi were more prominent during the intermediate decomposition stages (12 weeks), particularly in the larger fractions, while bacteria dominated the later phases. Organic amendments, especially when combined with clay and fertilizer, enhanced microbial diversity and functional gene abundance related to carbon degradation (endoglucanase) and nutrient cycling (ureC). Overall, the co-application of clay and hay residue improved soil structure, microbial activity, and nutrient retention, demonstrating synergistic benefits for restoring sandy soil fertility.

**Keywords:** Clay, Hay residue, Fertilizer, Aggregation, Fungi, Bacteria, Sandy soils

**Acknowledgments**

This study was funded by the Soil Science Challenge Grants Program (Project 4-H4T24R2) through the Australian Government Department of Agriculture, Fisheries and Forestry, contributing to the National Soil Strategy and the National Soil Action Plan. The author also acknowledges support from an Australia Awards Scholarship.

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# Impacts of sample storage conditions on extracellular DNA-based assessments of soil biodiversity

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**ABSTRACT**

The study of soil biodiversity is crucial to understand the effects of management practices on soil functions that are essential for the delivery of ecosystem services. Innovative methods of extracellular soil environmental DNA (exDNA) extraction using a phosphate buffer method provide a promising approach to study the near totality of soil organisms from large volumes of soil. However, despite its application in numerous soil biodiversity studies, little research has been done with regards to procedural aspects of this method, such as the importance of sample storage conditions. While storage at elevated temperatures can promote exDNA degradation and induce shifts in microbial communities that deviate from conditions in the studied environment, freezing soil samples leads to cell lysis and the subsequent release of intracellular DNA into the extracellular milieu, which may be undesirable. Furthermore, it is unknown to what extent changes in the exDNA fraction occur over time during storage and how they may affect estimates of soil community structure and diversity. This study investigated such potential effects of sample storage time and temperature on soil exDNA analyses. Aliquots of a composite soil sample from an arable field were stored at room temperature (~20°C), 4°C or -20°C for a duration of 1, 3, 7, or 14 days. We evaluated the effects of the different treatments on the quantity of phosphate buffer-extractable exDNA, as well as on biodiversity metrics of microbial and faunal communities derived from exDNA metabarcoding analyses. The results of this experiment will contribute to optimizing exDNA-based protocols for multi-taxa biodiversity surveys and research on best practices in sustainable soil management.

# A data-driven methodology to identify key biological indicators linked with ecosystem services in agricultural soils

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**ABSTRACT**

Soil biodiversity is key for multiple soil ecosystem services. However, soil thousands of species interact within soils. Current uncertainties on these mechanisms hamper the definition of effective measures to maintain soil health. This study presents a data-driven methodology where species interactions and their links with ecosystem services are inferred from experimental data. We use a dataset including over 180 samples from agricultural soils across Continental, Atlantic, Mediterranean, Nemoral, Pannonian, Lusitanian, Boreal and Atlantic pedoclimatic regions. Biodiversity was measured by metataxonomic analysis of bacteria (16s rRNA), fungi (ITS) and nematodes (ITS). Ecosystem services were evaluated based on physicochemical variables linked to (I) carbon sequestration and storage, (II) nutrient cycling and fertility, (III) water retention, (IV) water infiltration and erosion reduction, and (V) contamination reduction.

Based on co-abundance networks, we identified communities of closely related taxonomic units using *spin glass*. It was hypothesized that network communities represent ecosystems within the soil, which might be involved in ecosystem function regulation. Communities consistently include interactions between kingdoms (bacteria, fungi and/or nematode), demonstrating the complexity of soil ecosystems. Using sparse projection to latent spaces (*sPLS*), we identified communities relevant for nutrient cycling and fertility across every pedoclimatic region, carbon sequestration and storage in every region but Atlantic, water retention in the Mediterranean region, water infiltration and erosion reduction in Atlantic and Lusitanian regions, and contamination reduction in Mediterranean regions. Their role in these ecosystem services was verified post-hoc using data from the scientific literature that included *in vitro* or molecular analyses.

Therefore, this study presents a paradigm shift both in the computational methods for the analysis of soil ecosystems, as well as in the interpretation of soil biodiversity. Rather than focusing on key species as providers of ecosystem services, this study advocates for the characterizing biological communities whose interaction regulate soil ecosystem services. This advances our understanding of soil ecology and might, in the long term, improve measures for assuring soil ecosystem services.

**Acknowledgments**

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# Biochar-Compost Interactions: Impacts on Soil Health and Plant Performance in Regenerative Organic Systems

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**ABSTRACT**

Biochar, a carbon-rich material produced from organic biomass, has been shown to improve soil structure, enhance water retention, and stimulate microbial activity. When combined with compost, its effectiveness is often amplified. However, key knowledge gaps remain regarding optimal application rates, long-term effects, and interactions across soil types and crop species. We investigated the impact of biochar, alone and in combination with compost, on soil health and sweet pepper (*Capsicum annuum* L.) growth and fruit production under controlled glasshouse conditions at Kutztown University, Kutztown, Pennsylvania, United States in summer 2025. A pot experiment was conducted using silt loam soil collected from a certified regenerative organic field at Rodale Institute, with three rates of biochar (0, 12.4, and 24.8 t $ha^{-1}$) and two rates of compost (0 and 12.4 t $ha^{-1}$), arranged with seven replications. Sweet pepper plants were grown in 28 cm tall and 25 cm wide pots after treatment application. Data collection included soil chemical properties, soil health indicators, carbon fluxes and pools, and plant growth responses. Findings from this study will support the best practices for integrating biochar and compost into regenerative organic systems to improve soil fertility, crop resilience, and productivity. Detailed results will be presented at the 23rd World Congress of Soil Science Conference.

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# Soil Enzyme Activities and Microbial Biomass Biomarker Associated with the Integration of Cereal Rye to Improve Tomato Soil-Borne Disease Suppression and Yield

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**ABSTRACT**

Agronomic management systems for improving soil and tomato health are needed for sustainable tomato production. The goals of this research study are based on the integration of holistic and ecologically sound agricultural management components, which include arbuscular mycorrhizal fungi (AMF) and cover crop (rye grass) to enhance soil health and tomato soil-borne disease control. A 3-year field experiment was conducted at The Ohio State University's Waterman Farm in Columbus/Ohio/USA on tomato growth using 2 main plot treatments: 1) rye cover crop, 2) *Fusarium* disease inoculation, and 3 split-plot treatments: a) AMF inoculation, and b) fungicide application, c) untreated control.

Soil samples were collected from the tomato root zone in 0 to 20 cm depths and were analyzed for microbial Ester-Linked Fatty Acid Methyl Esters (EL-FAME), as well as soil enzyme activities such as arylsulfatase, β-glucosaminidase, acid phosphatase, and glucanase activities. Arylsulfatase and β-glucosaminidase enzyme activities increased during the season and appear to be sensitive indicators for cover crop management and *Fusarium* disease suppression. EL-FAME analysis revealed that soil microbial biomass was stimulated by cover crop treatment, and AMF increased due to cover crop and reduction in *Fusarium* infection, indicating these treatments have induced disease suppressive soils.

**Acknowledgments**

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# Soil Health Bioindicators: Sequences to Services across Europe for wide-scale monitoring

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**ABSTRACT**

Soil biodiversity is a primary driver of soil health, yet there is a need for a systematic pipelines to convert raw information into decision-ready indicators. Here, I present the findings of the EU HORIZON project: SOB4ES project. This is a European consortium of 15 partners with the principal aim to link soil biodiversity with ecosystem services at continental scales. Comprehensive soil biodiversity sampling from over 430 sites across nine Pedo-climatic zones was carried out between Oct-Dec 2023. In processing samples, we use AI machine-learning computer vision and verification of microbial and faunal based eDNA data analysis, we develop an end-to-end framework that translates multi-taxa sequencing outputs into functional bioindicators linked to ecosystem services.

I present findings of spatial distribution patterns across regions, land-uses and management practice intensity. By doing so, we can infer the driver of biotic groups and their interactions with abiotic parameters. We assessed total soil biodiversity across the trophic web from macrofaunal earthworms, mesofaunal microarthropods and enchytraeids, to microfaunal nematodes and protists, to microbiomes. To support application at scale, we align the biodiversity data with environmental parameters and aid determination of the resolution and aggregation required for monitoring.

Early findings indicate contrasting patterns of physical and chemical drivers and influencers across land-use types, depending on abiotic factors modifiable by the environment, and ii) those by biotic interactions. Other outcomes including potential presence/absence for certain functional biotic groups may be practical recommendations for wide-scale monitoring across land-use types. We also highlight biodiversity hotspots with potential conservation focus. Ultimately, these will inform regulatory reporting and conservation planning in both agricultural and natural ecosystems.

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# A Next-Generation Approach to Soil Health in Brazil

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**ABSTRACT**

Soil health is a central component of agricultural sustainability and global climate mitigation strategies. However, critical knowledge gaps remain in the integrated understanding of soil microbiomes across highly productive regions of the Global South. The NAPI Agrogenomics: Soil Microbiome Program emerges as the largest and most comprehensive initiative ever undertaken in these countries, combining *shotgun* metagenomics, spectroradiometry, remote sensing, and chemical, physical, and biological analyses, including emerging contaminants, to characterize microbial biodiversity and function across 12 million hectares of agricultural lands in Paraná State, Brazil. The project will conduct semi-annual sampling over five years, totaling approximately 8,000 analyses and covering both mineral soil and the plastisphere.

Grounded in literature emphasizing the role of soil–climate–microbe interactions in nutrient cycling, carbon stabilization, and resilience (Banerjee et al., 2023), the project also addresses emerging contaminants like microplastics, which alter soil microbial structure (Zhang & Liu, 2022). AMR genes will be monitored via metagenomics, following One Health principles. The first sampling (completed June 2026) followed edaphic, climatic, and productivity criteria, enabling precise spatial microbial characterization. The resulting dataset will feed machine-learning models to estimate soil health, carbon stability, management and pesticide impacts, and AMR patterns, supporting an open platform for farmer-focused recommendations.

Unprecedented in scale, temporal depth, and technical integration within the Global South, the NAPI Agrogenomics: Soil Microbiome Program establishes a new benchmark for multi-omics soil studies and lays the foundation for a regional digital agro-environmental atlas. The program serves as a model for scalable, data-driven soil monitoring systems in tropical agriculture. The initial results demonstrate the transformative potential of combining genomics, spectroscopy, and spatial data to enhance agricultural resilience and inform public policies grounded in scientific evidence.

**Acknowledgments**

This research is part of the NAPI Agrogenomics – Soil Microbiome Network, funded by the Government of the State of Paraná (Brazil) through SETI and managed by Fundação Araucária. The network brings together over 30 researchers from multiple institutions to advance soil microbiome and soil health research in agricultural landscapes. We acknowledge the financial and institutional support enabling the development of this multi-year integrative project.

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# Soil organisms from multiple trophic levels regulate respiration in dryland purple soil

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**ABSTRACT**

Increasing soil organic carbon (SOC) content in cropland is essential for sustainable crop production, as it optimizes nutrient cycling and mitigates greenhouse gas emissions. However, SOC sequestration efficiency is primarily constrained by soil respiration, a process driven by diverse soil organisms. To investigate their regulatory roles, a long-term field experiment was conducted to compare four treatments: no fertilizer (CK), synthetic fertilizer (NPK), partial synthetic nitrogen replacement with pig slurry (OMNPK) or crop residue (RSDNPK). We measured *in-situ* $CO_2$ fluxes and characterized the soil organisms from multiple trophic levels (nematodes, protists, fungi, bacteria) via amplicon sequencing. A complementary incubation experiment with increased labile carbon addition (CN0, CN10, CN50 and CN100) was conducted to further explore the functional gene-level mechanisms. Results showed that soil respiration was the dominant contributor to global warming as indicated by the high quantity of $CO_2$ emissions, with the RSDNPK treatment exhibiting the highest values. Multi-trophic community of key functional guilds underlying $CO_2$ emissions varied significantly among treatments. They explained up to 35% of the variation in $CO_2$ fluxes from soil and were significantly influenced by protists. The incubation experiment revealed that high labile carbon input increased soil respiration, but reduced the alpha diversity of protists, fungi and bacteria by 21-80%, alongside weakened cross-trophic interactions. The composition of carbon-cycling genes was positively correlated with soil respiration, with 23 key functional genes identified mainly for decomposing of hemicellulose, cellulose, lignin and starch. A ranking analysis indicated that bacterial and protist biodiversity were the top two factors in moderating these decomposition pathways underlying soil respiration. In conclusion, preserving multi-trophic biodiversity, particularly of bacteria and protists, is essential to mitigate excessive soil respiration. Therefore, agricultural management practices should aim to maintain balanced carbon inputs to support a diverse soil food web, thereby promoting more efficient soil carbon sequestration.

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# Mycorrhizal fungal communities in Sarayaku territory: Impact of traditional agricultural practices

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**ABSTRACT**

Amazonian soils harbor exceptionally high fungal biodiversity, critical for plant health and ecosystem functioning. This study, conducted in the Kichwa indigenous territory of Sarayaku (Ecuador) along the Bobonaza River in the Napo moist forest ecoregion, documents soil fungal communities across a successional chronosequence. Twenty-five soil samples were collected from three ecosystem types: primary forest (11 samples), secondary forest (7), and traditional chakra agroforestry systems (7). Using environmental DNA (eDNA) metabarcoding, a total of 5,172 fungal OTUs were identified, including 381 arbuscular mycorrhizal (AM) OTUs (40% unknown, likely undescribed) and 39 ectomycorrhizal (EcM) OTUs (10% unknown). Overall fungal diversity was highest in primary forests (–3,600 OTUs) and lowest in chakras (–2,400), with rapid recovery in secondary forests, underscoring the resilience of the chakra system. AM fungal richness being significantly higher in primary forests (298 OTUs) than in chakras (137), although community composition did not differ significantly. EcM richness showed no significant variation across ecosystems (9–13 OTUs per habitat). Soil factors strongly influenced diversity: high nitrogen, low pH, and elevated aluminum, iron, and copper levels were associated with reduced AM and EcM diversity, likely linked to short-term effects of slash-and-burn in chakras. RSCI analysis highlighted rare, potentially endemic taxa such as Russula aucarum. These results provide a critical baseline for long-term monitoring and data-driven restoration, demonstrating that indigenous chakra practices support the preservation and rapid recovery of high mycorrhizal diversity. Such traditional systems offer valuable models for global regenerative agriculture. Future work should include longitudinal studies and sampling of sacred sites to further explore mycorrhizal interactions and potential alleviation of metal toxicity in acidic soils.

**Keywords:** Mycorrhizal fungi, Fungal biodiversity, Sarayaku, Chakras, Amazonia.

**Acknowledgments**

The expedition team included scientists from SPUN (Society for the Protection of Underground Networks), local Ecuadorian researchers (Dr. Adriana Corrales, Dr. Jessica Duchicela), Sarayaku community members, and MOTH collaborators.

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# Auxotrophic Bacteria in Maize Rhizosphere and Bulk Soil: Insights into Microbial Dependencies

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**ABSTRACT**

Plants release amino acids and other compounds that shape rhizospheric bacterial communities, potentially enriching auxotrophic bacteria that cannot synthesize certain amino acids and depend on external sources. We hypothesize that auxotrophs are more abundant in the maize rhizosphere than in bulk soil. To test this, we used a dependency-based cultivation strategy to evaluate auxotrophy profiles in maize rhizospheric and bulk soil communities obtained from a mesocosm experiment conducted in a greenhouse for 50 days. Soil suspensions were inoculated into enrichment media prepared as minimal formulations containing only minerals and two carbon sources (pyruvate and glucose). These media were supplemented with amino acids and vitamins, organized into six chemical groups based on their structural features. The suspensions were added at $10^{-2}$, $10^{-4}$, and $10^{-6}$ dilutions, and only the latter two dilutions allowed clear discrimination of growth responses as a function of the amino acids supplied. Rhizospheric communities preferentially consumed aliphatic non-polar, polar and negative, and polar non-charged groups, while bulk soil communities favored aliphatic non-polar, polar and positive, aromatic, and polar non-charged compounds. Both environments strongly utilized aliphatic non-polar amino acids such as methionine, a described cooperative metabolite. Lysine and phenylalanine, also described as cooperative amino acids, were more associated with consumption in bulk soil. We are currently isolating auxotrophic bacteria from these enrichment cultures, and subsequent metabolomic analyses will elucidate metabolic dependencies and their roles in plant–microbe interactions.

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# Soil management drives microbial diversity patterns and community structure under Cd and Cr contamination

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## ABSTRACT

Microbial communities are key indicators of soil ecological functioning and respond sensitively to both land-use systems and contaminant pressures. Heavy metals such as Cd and Cr can disrupt microbial community structure, suppress functional diversity, and impair nutrient-cycling processes; however, the magnitude of these effects is strongly modulated by soil properties and management history. This study evaluates whether a more conservative agricultural system, characterized by long-term no-till and diversified cover-crop mixtures in soybean-maize rotations, confers greater resilience of the soil microbial community to metal contamination compared with its native forest and the same soil under the same crop rotations with limited cover-crop diversification.

Soils were incubated for 45 days under three treatments: control, Cd (3 mg $kg^{-1}$), and Cr (150 mg $kg^{-1}$). These metal doses align with Brazilian regulatory limits and represent environmentally relevant contamination. Bacterial communities were profiled via 16S rRNA gene (V4) sequencing following DNA extraction with the PowerSoil Pro Kit. Alpha-diversity (richness, Shannon, Simpson) and beta-diversity (Bray-Curtis PCoA) metrics were quantified and statistically evaluated to determine management-specific microbial responses. Contrary to expectations, neither Cd nor Cr significantly altered microbial diversity or community composition. Alpha-diversity remained stable across treatments within each management system, indicating that microbial richness and evenness were unaffected by metal addition. PCoA results reinforced this pattern: within each management system, control, Cd, and Cr treatments clustering together with no detectable shifts in community structure. The lack of treatment effects is consistent with rapid sorption and transformation of Cd and Cr into less bioavailable forms, especially given that Cr was added as the less reactive $Cr^{3+}$ species. Moreover, both agricultural soils were well-managed, chemically fertile, and exhibited high soil health indices, conditions known to enhance functional redundancy and buffer microbial communities against short-term disturbances. Despite their total concentration, these results show that the metals were not sufficiently bioavailable to cause short-term disruptions in soil microbial community.

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# The role of microorganisms in changing the properties of eroded soils

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**ABSTRACT**

The paper presents the results of research on the influence of erosion processes on the agrochemical and microbiological properties of the soil in different seasons of the annual cycle. The objects of the study are sod-podzolic (Umbric Retisols (Abruptic)) and agro-gray (Greyzemic Phaeozems (Albic)) soils of varying degrees of erosion (Moscow region).

It has been established that the degradation of the physical and agrochemical parameters of sod-podzolic soil, which occurs as a result of erosion processes, leads to a change in microbiological parameters. A decrease in the abundance and species diversity of fungi and actinomycetes occurs with an increase in the degree of soil erosion. Significant differences were found in the taxonomic composition of microbial communities of unwashed and washed-away soils: the Sorensen species similarity coefficient does not exceed 0.42 for fungi and 0.30 for actinomycetes. Taxonomic units of mycelial microorganisms have been identified. Among fungi, these are representatives of the genera *Aspergillus*, *Cladosporium* and *Scopulariopsis*, and among actinomycetes, by *Streptomyces malachitospinus*, *S. candidus* and *Micromonospora aurantiaca*.

Investigations carried out on agro-gray soil showed that the content of alkaline hydrolyzable nitrogen, exchangeable potassium and mobile forms of phosphorus depended both on the degree of soil washout and on seasonal fluctuations. Analysis of the chemical composition of soil organic matter showed that in the summer there was an increase in carboxylic, carbonyl and aromatic components, and in other periods of carbohydrate fractions. In the agro–gray soil, bacterial biomass reserves varied from 27 to 96 kg*ha$^{-1}$, fungal biomass from 10 to 357 kg*ha$^{-1}$. The dynamics of the number of bacteria in the agro-gray soil was determined to a greater extent by the degree of washout (56% of the total dispersion) than by the season (36%). The abundance of bacteria and actinomycete mycelium decreased in the range: non-washed>slightly washed>medium washed. The annual average values of prokaryotic biomass decreased from 76 kg/ha in non-washed, to 56 kg/ha in slightly washed and 41 kg/ha in medium washed. Losses of prokaryotic biomass relative to non-washed soil were to 26% in slightly washed and 46% in medium washed soil. With an increase in the degree of washing, both fungal and bacterial biomass decreased in the range of non-washed>slightly washed>medium-washed. Washed-away soils lost an average of 50% of bacterial and 59% of fungal biomass relative to non-washed soils. In the studied soils, the level of potential respiration (SIR) exceeded the level of actual respiration (BR) by 2-33 times.

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# Harnessing Soil Cyanobacteria for Resilient Agriculture: Evidence from a 20-Year Mediterranean Orchard Trial

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**ABSTRACT**

Soil cyanobacteria are increasingly recognized as key drivers of sustainable agriculture thanks to their wide range of ecological functions. These ancient, photosynthetic microorganisms participate actively in biogeochemical cycling, enrich the topsoils with organic matter, and supply essential nutrients that support plant development. By producing extracellular polymers and diverse bioactive metabolites, they help create stable microhabitats, improve soil structure, and foster synergistic interactions with both the rhizosphere and other beneficial soil microbes. Their presence is therefore tightly linked to soil resilience, fertility, and long-term ecosystem functioning.

This study investigated the taxonomic composition and functional potential of soil cyanobacterial communities in a Mediterranean olive (*Olea europaea* L.) orchard in a semiarid, hilly area of Ferrandina (Basilicata Region, southern Italy). The orchard has been managed for over twenty years under two contrasting systems: sustainable ($S_{mng}$) and conventional ($C_{mng}$), which differed markedly in soil tillage and cover, crop residues management, fertilization and irrigation. Cyanobacteria were sampled across several representative topsoil locations (0-5 cm depth) within the orchard, and then cultured and isolated on selective nitrogen-enriched media and, to promote the growth of diazotrophic strains, on nitrogen-free media.

Sustainably managed soils hosted significantly higher cyanobacterial populations ($0.408 \times 10^2$ g$^{-1}$ soil in $S_{mng}$ vs. $0.240 \times 10^2$ g$^{-1}$ in $C_{mng}$), as counted by the densitometric and MPN methods. Light microscopy and 16S rRNA metagenomic analyses revealed clear compositional differences between systems. In the $S_{mng}$ plots, genera such as *Anabaena* and *Nostoc*, known for their nitrogen-fixing ability and ecological versatility, were more abundant and contributed substantially to community structure. Management also affected cyanobacterial metabolic profiles: cyanobacteria from the $S_{mng}$ soils showed an upregulation of the biosynthetic pathways associated with secondary metabolites, including alkaloids, phenylpropanoids, phytohormones, phytoalexins, polyketides, and terpenes, which are widely recognized for their roles in plant growth promotion and defense activation.

Overall, the findings demonstrate that sustainable soil management enhances both the diversity and functional capacity of soil cyanobacteria. These microorganisms emerge not only as crucial contributors to ecological processes and biodiversity maintenance but also as promising natural allies for improving soil health and crop productivity, two fundamental ecosystem services that were markedly higher in the $S_{mng}$ system compared with the $C_{mng}$ one.

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# Permanent vegetation cover as a strategy to enhance soil multifunctionality in perennial crops in the Mediterranean basin

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## ABSTRACT

Agricultural intensification in the Mediterranean basin has led to soil degradation, compromising its ability to perform essential functions, creating a need for sustainable strategies. This study assessed the use of vegetation cover on the alleys of perennial crops compared to conventional tillage on soil multifunctionality in three woody crops: almond, olive and fruit trees. To evaluate multifunctionality, we used the following categories: i) soil quality by visual soil assessment; ii) nutrient cycling; iii) organic matter decomposition; iv) plant productivity (biomass of vegetation); and v) plant health (estimated by the abundance of microorganisms potentially producing siderophores). Multifunctionality was assessed by using three indices (Z-scores, thresholds, and clusters). Finally, differences and the impact of different biotic and abiotic properties on the multifunctionality index were evaluated. The three indices showed similar results. Farms with vegetation covers showed higher multifunctionality index than those with tilled alleys, as reflected by the z-score (0.178 ± 0.450 and -0.178 ± 0.308), threshold (0.450 ± 0.394 and 0.308 ± 0.313) and cluster indices (0.187 ± 0.435 and -0.187 ± 0.301). The results obtained showed that the abiotic factors temperature and cover crop year increased the multifunctionality index. Increases in soil clay content, bulk density, calcium carbonate, pH, altitude, and tillage depth led to a decrease in multifunctionality. Furthermore, we found a negative relationship between soil microbial diversity with the multifunctionality index, estimated using Pielou's evenness for fungi and bacteria and the Shannon index for fungal diversity. In conclusion, although certain abiotic soil properties may improve multifunctionality, higher microbial diversity did not translate into greater multifunctionality in Mediterranean systems. This suggests that, in this region, assessing the functional composition of microbial communities may provide more meaningful insights than focusing exclusively on overall biodiversity. Moreover, the transition to systems with permanent vegetation cover in alleys is presented as an effective strategy to decouple agricultural production from soil degradation, with the duration of vegetation cover, tillage, climatic conditions, clay content, pH, carbonate and bulk density being key factors in maximizing multifunctionality in Mediterranean agroecosystems.

**Acknowledgments**

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# Phosphate-Solubilizing Bacteria Enhance Sugarcane Growth: High-Potential Candidates for Sustainable Biofertilizer Development

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**ABSTRACT**

This study selected four high-efficiency phosphate-solubilizing bacteria isolated from sugarcane cultivation areas in Sa Kaeo Province, Thailand. These strains—*Kosakonia radicincitans*, *Bacillus subtilis* OTEB25, *Bacillus subtilis* SKUAST1, and *Enterobacter* sp.—exhibited high phosphate-solubilizing activity (447–748 µg/mL) in previous research. The objectives were to determine the optimal bacterial concentration and environmental conditions for phosphate solubilization and to examine the potential of PSB to promote plant growth. The results showed that the optimal initial cell concentration for phosphate solubilization was $10^8$ CFU/mL. The bacteria were able to solubilize phosphate in culture media under both acidic and alkaline conditions with pH range of 5–9, achieving solubilization levels of 212.5–787.5 µg/mL. However, they were unable to grow or solubilize phosphate under strongly acidic conditions (pH 4.0). Among the tested isolates, *Kosakonia radicincitans* and *Bacillus subtilis* SKUAST1 demonstrated greater pH stability than the others and were therefore selected for further evaluation in sugarcane. Greenhouse experiments revealed that inoculation with these strains, either individually or in combination with rock phosphate, enhanced sugarcane growth—including plant height, fresh stalk weight, stalk length, and stalk diameter. Combined inoculation with rock phosphate significantly increased phosphorus uptake and soil available P relative to the control. These bacteria were able to survive, solubilize phosphate, and promote sugarcane growth more effectively than the control treatment. Therefore, *Kosakonia radicincitans* and *Bacillus subtilis* SKUAST1 are considered promising candidates for field-scale trials to evaluate their effects under real cultivation conditions, with potential for future development as biofertilizers.

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# Model-Driven Microbiome: Next-Gen Soil Bioremediation

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**ABSTRACT**

Global environmental co-contamination, fueled by expanding industry and agriculture, challenges ecological restoration. Though microbial consortia outperform single strains, rational design of stable, pollutant-adaptable communities remains a microbial ecology gap. Current methods rely on empirical trial-and-error, lacking systematic integration of native microbial functions or metabolic interactions, limiting real-world remediation efficacy.

We developed a "top-down & bottom-up" framework: Top-down analysis transformed natural microbiomes into functional ones via stress acclimation, screening keystone species for synthetic communities. We also created the genome-scale metabolic modeling (GSMM) tool SuperCC (Super Community Combination), which deciphered inter-strain interactions and simulated remediation performance via bottom-up modeling. Using 18 natural keystone species, SuperCC-supported engineered microbiomes enhanced herbicide (single contamination) degradation, validating its utility. For co-contamination, we expanded SuperCC applications: Modeling 6 key strains' metabolic behaviors and integrating multi-omics clarified interaction networks. We found secretory products of broad-spectrum resource-utilizing bacteria drive interspecific synergy, and indigenous keystone strains stabilize community function. These insights led to the novel DHP-Com (Degrader-Helper-Potentiator) synthetic microbiome paradigm, where "potentiators" (species with stable habitat abundance) boost community ecological adaptability. DHP-Com-based synthetic microbiomes achieved breakthrough remediation efficiency in multi-pollutant soils, resolving unstable synthetic community function under co-contamination.

With scenario-specific SuperCC application, this study links microbiome engineering pathways from single to co-contamination. It verifies model-driven technology's applicability across pollution gradients, provides a "natural regulation to synthetic design" progressive solution for next-gen soil bioremediation, and bridges microbial metabolic modeling with practical pollution control.

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# Belowground nutrient transfer between Scots pine and bilberry mediated by ectomycorrhizas

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**ABSTRACT**

Ectomycorrhizal fungi (EMF) are essential for plant-soil nutrient cycling in forest ecosystems, forming symbiotic relationships with plant roots. They receive 10-30% host plant photosynthate and in return improve plant nutrient acquisition. EMF symbiosis can establish common mycorrhizal networks (CMNs), connecting multiple plant hosts from the same or different species. CMNs have been found to enhance plant productivity and crucial in carbon sequestration. However, the quantity of the resources exchanged between plants and who manipulates the exchanges remain unanswered. Therefore, it's significant to investigate CMNs role in belowground nutrient cycling and how it relates to the host species identity.

This study aims to assess 1) the significance of carbon and nitrogen transfer through CMNs between pine and bilberry, 2) whether the interaction of different plant species affect their growth performance. One-year-old seedlings of Scots pine (*Pinus sylvestris L.*) and bilberry (*Vaccinium myrtillus*) were planted in the custom-made pots, which were divided equally with three types of barriers: solid barrier (no connection), 50μm mesh (roots blocked) and no-barrier (full connection). The seedlings were planted from October 2023 to October 2024 in three combinations: pine-bilberry, pine-pine, bilberry-bilberry. Labelling with $^{13}CO_2$ and $^{15}N$-needle-litter were performed for tracing the nutrient cycling. To quantify the carbon transferred by fungal hyphae, soil microbial biomass total C and $^{13}C$ were measured, alongside the plant photosynthesis and $^{13}C$ in needles/leaves. Plant productivity was evaluated through shoot and roots biomass. Microbial carbon use efficiency was analyzed using $^{18}O$-$H_2O$ to determine SOC stabilization. under snow exclusion. To further study changes in soil microbial community, the fungal Internal Transcribed Spacer (ITS2) and bacterial 16S from the isolated DNA was sequenced by Illumina MiSeq platform.

Preliminary results will be presented in the presentation.

**Keywords:** Ectomycorrhizal fungi, common mycorrhizal networks, nutrient cycling, Scots pine, *Vaccinium myrtillus*

# Relations of Soil Microbe-Resource Stoichiometry Varied Across Soil Depth

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**ABSTRACT**

As a critical carrier for agricultural production, the stoichiometric balance between soil microorganisms and resources (carbon, nitrogen, phosphorus) in black soil ecosystems serves as the core regulatory link governing nutrient cycling and organic carbon pool stability. Tillage disturbances induced by agricultural reclamation not only alter the spatiotemporal distribution patterns of soil nutrients but also profoundly disrupt the stoichiometric coupling between microorganisms and their resources. However, existing research on microbe-resource interactions has predominantly focused on single temporal or spatial sequences, leaving the dynamic evolution of these relationships under dual spatiotemporal dimensions and the underlying microbial adaptation mechanisms insufficiently addressed. This study investigated black soil farmlands with different reclamation ages (65, 85, and 105 years) to explore the dynamics and response patterns of microbe-resource stoichiometry across soil layers (0—50 cm). Results revealed that the C:P stoichiometric imbalance between microorganisms and their resources significantly intensified with increasing reclamation age, with the most pronounced effects observed in the topsoil (0–20 cm). In response to this imbalance, microbial communities exhibited a dual adaptation strategy of "homeostasis maintenance-functional adjustment": (1) the microbial biomass C:N ratio remained relatively stable with no significant fluctuations, reflecting strong homeostatic characteristics; and (2) microorganisms adjusted the vertical distribution of extracellular enzyme activities (e.g., significantly increasing the ratio of phosphorus-acquiring enzymes to carbon-acquiring enzymes in the topsoil) to acquire limiting nutrients. These findings indicate that the spatiotemporal dynamics of microbe-resource stoichiometry in black soil agricultural ecosystems are synergistically driven by the "cumulative effect of reclamation age and vertical differentiation of soil depth." Furthermore, microbial homeostatic regulation and enzyme activity optimization represent key adaptation mechanisms for sustaining ecosystem functionality. This study clarifies the evolution of microbe-resource stoichiometric balance following black soil reclamation, providing a scientific basis for soil fertility management and organic carbon pool protection in black soils across different reclamation stages and soil layers.

# Variations in synergistic benefits among different intercropping systems: evidence from crop, soil and soil biota in agroecosystems

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**ABSTRACT**

Intercropping has been increasingly adopted to mitigate agricultural land degradation caused by long-term monocropping. It leverages the synergistic traits of different plant species to optimize aboveground and belowground resource utilization, thereby significantly enhancing agricultural productivity and ensuring long-term sustainability. However, studies on the synergistic regulation mechanisms among crop, soil and soil biota remain scarce in different intercropping systems. To elucidate how intercropping systems modulate crop-soil-soil biota, both peanut/maize and alfalfa/maize combinations were selected to determine and compare crop growth performance, soil characteristics, and key soil nematode metrics including their abundance, community composition and food web energy structure. Studies have shown that peanut/maize intercropping resulted in a higher land equivalent ratio and significantly increased soil nitrogen levels compared with alfalfa/maize intercropping. Both intercropping systems increased soil nematode abundance compared with monocropping. Meantime, the richness, diversity, maturity and structure indices of soil nematode communities were enhanced in the maize rows of both intercropping systems. Furthermore, intercropping also altered carbon flux dynamics and improved the uniformity of carbon flux within the soil nematode food web in the peanut rows. Partial least squares path modeling revealed that peanut/maize systems improved soil nematode communities through direct and indirect pathways by enhancing crop competitiveness and optimizing soil properties, whereas alfalfa/maize exhibited weaker effects. In conclusion, the peanut/maize system exhibited both strong selection effects aboveground and complementarity effects belowground, as evidenced by the improved soil characteristics and the amplification of ecological regulation pathways among crop, soil, and soil biota. Peanut /maize intercropping was shown to generate significant aboveground and belowground synergies which both boost crop yields and maintain optimal system productivity, providing a cost-effective and sustainable intensification strategy for modern agroecosystems.

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# Crop Coexistence Redefines Belowground Microbial Assembly Toward N-Cycling Archaea and Fungal Resource Networks

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## ABSTRACT

Barley-pea intercropping has the potential to restructure soil microbial communities and nutrient cycling functions, with responses shaped by soil compartment, management system, and year. We quantified the abundance of microbial taxonomic markers (bacterial and archaeal *16S rRNA* genes, fungal *ITS*) and key nitrogen cycling genes (*nifH,* archaeal and bacterial *amoA*, *nirK, nirS*, *norB*, *nosZ*) in rhizosphere and bulk soils over two growing seasons under conventional and organic management with and without manure, within a long-term crop-rotation experiment established in 1997.

A clear pattern emerged in which archaeal groups, archaeal *amoA*, and total fungi showed the strongest and most consistent responses to crop treatments. In the rhizosphere, intercropping and legume monoculture frequently elevated archaeal 16S and archaeal *amoA* abundances across both years, particularly in organic systems, indicating a strong recruitment or enrichment of ammonia-oxidizing archaea by plant roots. Fungal *ITS* abundance was also consistently increased by legumes and intercropping, both in the first year across management systems and in the second year under organic management with manure. Denitrification-related genes exhibited more targeted shifts, including higher *nirK* in legume treatments in the first year under conventional management and elevated *norB* under intercropping in organic systems with manure. Conversely, *nifH* declined under legumes in the second year in organic systems without manure, suggesting limitations on free-living nitrogen fixation under certain nutrient contexts.

Bulk soil responses diverged from those of the rhizosphere and were strongly year dependent. In the second year under conventional management, intercropping and legumes increased archaeal and bacterial *amoA*, while fungal *ITS* and bacterial *16S* were elevated in the first year. Some functional genes declined in bulk soil under intercropping, including *nosZ* in organic systems without manure.

Overall, barley-pea intercropping significantly restructured soil microbiomes, with the strongest and most consistent effects seen in ammonia-oxidizing archaea and total fungi. These findings suggest that plants and their associated soil environments selectively recruit microbial groups that enhance specific nutrient cycling functions, especially nitrification and fungal-driven resource turnover. The results demonstrate that crop diversification acts as a biological filter shaping microbial communities and functions, but the magnitude and direction of these effects depend on soil compartment, nutrient management, the long-term rotation context of the site and interannual variability.

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# Soil microbial community structure in reclaimed and unreclaimed post-mining areas

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**ABSTRACT**

Mining and quarry activities have significant environmental impact on ecosystems over the years, especially when these activities are abandoned. Among others, new soils can form over mine wastes characterized by imbalanced texture classes or chemical properties or high contents of heavy metals in the soils and in surrounding waters. In general, to assess the success of different reclamation activities, physicochemical properties are evaluated; however, few studies have focused on biological properties. In this study, we selected soils from unreclaimed and reclaimed areas in Spain: a Cu abandoned mine area (NW Spain) and a Pb/Zn mine area (SE Spain). In both cases, mining activities were abandoned several decades ago. Remediation activities have been applied several years after abandonment. They were focused on the creation of artificial soils (Technosols) by using the aided phytostabilization technique, which combines heavy metal-tolerant plants (rhyzostabilization) with organic or inorganic amendments (chemical stabilization), aiming to reduce soil metal bioavailability while improving soil health. Soil samples (0-30 cm depth) have been collected from both reclaimed and unreclaimed areas, and physical, chemical, and biological properties have been measured. In general, soil physicochemical properties have improved after reclamation, including reduced bioavailable metal concentrations (Cu, Pb, Zn). In the case of biological properties, changes in the soil microbial community have been assessed using phospholipid fatty acid (PLFA) analysis. The Phospholipid Fatty Acid (PLFA) analysis revealed that the microbial community improved after amendments and was aided by phytostabilisation activities. In both restored mining areas, the biomass of Total PLFAs, Bacteria (including Gram+ and Gram-), and Fungi (Arbuscular mycorrhizal fungal, Zygomycota, and Ascomycota/Basidiomycota groups) was significantly higher than in non-restored areas ($p < 0.05$, t-test). These groups exhibited a 4–10-fold increase in biomass following restoration. However, the differences in Fungal/Bacterial and Gram+/Gram- ratios between treatments were not significant at the treatments carried out in the Cu mine. In general, reclamation activities improved soil physicochemical and biological properties in both abandoned mining areas, highlighting the potential of technosols and aiding phytostabilisation to reduce environmental impacts.

**Acknowledgments**

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# Conservation Tillage Reduces Mycotoxin Contamination in Black_Soil Maize Systems

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**ABSTRACT**

Maize mycotoxins represent a persistent global challenge to crop productivity, food safety, and public health. Tillage strongly shapes soil physicochemical conditions and microbial communities, thereby influencing the occurrence of toxin-producing fungi and mycotoxin accumulation. Although no-till is prevalent in the black soil region of northeastern China, its impact on maize mycotoxin contamination remains insufficiently understood. In this study, we combined a 14-year tillage experiment with multi-site field surveys across six farms in Jilin Province to evaluate maize kernel mycotoxins and soil fungal communities under conventional tillage (CT) and no-till (NT). Fourteen major mycotoxins were quantified using LC–MS/MS, among which deoxynivalenol (DON) and zearalenone (ZEN) were consistently detected across all samples over the two study years. NT markedly reduced the exceedance rates of DON and ZEN compared to CT. Moreover, NT enhanced fungal α-diversity, shifted community composition, and increased several ecologically important functional groups, indicating greater soil microecosystem stability. Overall, our study provides multi-site field evidence that NT lowers mycotoxin risks and promotes a more diverse and resilient soil fungal community. This supports the conclusion that NT is a sustainable management practice in black soil agroecosystems.

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# Soil Ecological Shifts Following Land Use Conversion to Agriculture in Southern Ethiopia

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**ABSTRACT**

Conversion of agroforestry systems to conventional agriculture is increasingly practiced in Southern Ethiopia due to rising food demand and economic pressures. This land-use change has critical implications for soil health, particularly concerning soil biota and microbial biomass carbon (MBC), which are key indicators of soil fertility and ecological sustainability. This study investigated the effects of agroforestry-to-agriculture conversion on soil biological properties at selected sites in Southern Ethiopia. Paired soil samples were collected from long-established agroforestry plots and adjacent agricultural lands that had been converted from agroforestry. Soil biota diversity and abundance were assessed, and microbial biomass carbon was measured using the chloroform fumigation-extraction method. The results showed a significant reduction in both MBC and soil faunal abundance following conversion. Agroforestry plots exhibited substantially higher MBC levels and greater diversity and abundance of soil organisms, including macrofauna and mesofauna. These differences are attributed to higher organic matter inputs, better moisture retention, and more stable microclimatic conditions in agroforestry systems. The findings emphasize that agroforestry systems support soil biological health more effectively than conventional agriculture. The loss of microbial biomass and soil biodiversity following conversion may impair soil functions such as nutrient cycling, organic matter decomposition, and long-term productivity. Overall, while the conversion of agroforestry systems to agriculture may provide short-term gains in food production, this trade-off is offset by the decline in soil quality and ecological resilience. Maintaining or integrating agroforestry within agricultural landscapes offers a more sustainable pathway that balances productivity with the preservation of soil health and ecosystem services, which is particularly vital in regions at risk of land degradation and food insecurity.

**Keywords:** Arbuscular mycorrhizal fungi, Glomalin Related Soil Protein, Microbial biomass carbon,

# Effects of Crop Residue Management Strategies on Soil and Root Nematode Assemblages

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**ABSTRACT**

Crop residues play a crucial role in maintaining soil health by enhancing organic matter, nutrient cycling, and microbial activity, thereby improving soil structure, water retention, and nutrient availability for sustainable maize production. Nematodes occupy multiple trophic levels and respond sensitively to environmental change, making them reliable bioindicators of soil quality and soil food-web condition. However, the effects of crop residue management on nematode communities differ between rhizosphere soil and root endospheres, and these compartment-specific dynamics remain poorly understood. Understanding these differences is essential for linking residue management to soil food-web functioning and plant health. A field study evaluated six residue management strategies: control (CK), no-tillage (NT), straw deep incorporation (SD), biochar (BC), and their combinations (NTBC, SDBC), to determine their effects on nematode community structure, diversity, and ecological indices in a maize agroecosystem over two consecutive growing seasons. A total of 64 nematode genera representing 40 families were identified across all treatments, enabling a comprehensive assessment of trophic and taxonomic responses. The rhizosphere soil sustained richer and more functionally diverse nematode assemblages, dominated by *Acrobeloides* and fungivores, with NTBC showing the highest Shannon diversity (H') and food-web complexity. Generic richness, taxonomic diversity, maturity index, and structural index were consistently higher in soil than in roots, indicating a more structured and resilient soil food web. In contrast, root habitats were low in diversity and dominated by *Ditylenchus*, which comprised up to 86% of the community, reflecting strong plant-parasitic pressure within root endospheres. Soil moisture, organic carbon, and total nitrogen were the key environmental drivers shaping nematode community structure, with fungivorous nematodes showing the strongest positive responses to improved soil conditions. Residue treatments showed clear trophic shifts: NT and NTBC enhanced fungal feeders and reduced plant-parasitic nematode abundance in roots and/or their trophic proportion in soil, whereas SD and SDBC increased the relative abundance of bacterivores and lowered overall plant-parasitic nematode indices. Dominant nematode genera served as effective ecological indicators of residue-driven changes and nematode pressure in maize. Overall, integrated residue management practices, especially NT and NTBC, promoted a structured and resilient soil food web while mitigating root pathogen pressure. These findings demonstrate that combining no-tillage with biochar incorporation offers a sustainable strategy to enhance soil ecological stability and regulate nematode communities in maize cropping systems.

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# The effects of nutrient-loaded biochar on earthworms in boreal agricultural soils

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**ABSTRACT**

Nitrogen loss from agricultural soil has led to various environmental hazards such as nitrogen (N) pollution, threatening water quality and contributing to eutrophication of aquatic ecosystems. Therefore, enhancing nitrogen use efficiency is an important approach for sustainable agriculture to meet the rapidly increasing food demand while minimising the harmful environmental effects. Nutrient-loaded biochars (NLB), a relatively recent concept, have the potential to simultaneously sequester atmospheric carbon in the soil as a means of mitigating climate change, provide slow and continuous nutrient release, and reduce nutrient loss. However, NLB's interaction with soil biota, especially earthworms, is essential to ensure the safe and efficient application of NLB in soil.

The study investigates the effect of organic nutrient-loaded NLBs on earthworm abundance, biomass, and mean weight in southern Finnish agricultural soils, loamy sand (Umbrisol). This was conducted in long-term continuous biochar field experiments at the University of Helsinki's Viikki Research Farm since 2011. NLBs were prepared from spruce biochar, activated with nitric acid and were then loaded with organic fertiliser (cattle slurry/meat bone meal). In a split-plot design, NLB treatment in Umbrisol was applied at two rates: 0 biochar and 20+30 t $ha^{-1}$. Fertiliser treatments include two types (no fertiliser and mineral fertiliser). NLB was applied to the topsoil layer in May 2023 before barley sowing in the soil. Post-harvest (2023 and 2025), earthworms were sampled from randomly selected locations within each plot using holes (25x25 $cm^2$, 28cm deep) by hand sorting and mustard extraction. Then counted, weighed, and identified based on morphological characteristics, such as pigmentation and clitellar development.

Preliminary data from the first year of application in 2023 did not indicate any significant short-term effects of NLB on the earthworm community. However, the higher application rates in loamy sand (20+30 t $ha^{-1}$) reduce earthworm biomass 1.29 g ($p=0.5$), indicating a potential threshold for safe use. A follow-up study in 2025, after two years of NLB application, now under analysis, would help to determine whether these effects persist or reduce over time. Moreover, the findings can also support climate change mitigation and ecological balance in boreal regions.

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# SOIL MICROBIAL BIOMASS AND COMMUNITY RESPONSE TO DIFFERENT PESTICIDES UNDER GREENHOUSE CONDITIONS

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## ABSTRACT

Various pesticides are widely used products for plant protection. However, their use exposes non-target organisms to undesirable effects. To assess their effect on the soil microbial biomass and community composition, a pot experiment was conducted in the greenhouse at the University of Debrecen, Hungary during spring from 23rd April to 23rd June 2025. Three kilograms of air-dried and sieved Chernozem soil collected from Látókép research station were weighed into plastic pots. A completely randomized design with five treatments (Trichoderma (10 ml per pot at a concentration of 0.027%), Lambda Cyhalothrin (0.6 g/pot), Cypermethrin (0.6 g/pot), Tefluthrin (0.5 g/pot) and control) and four replicates per treatment were used, totalling 20 experimental units. Prior to pesticide application, each pot was supplied with 50 ml of NPK fertilizer solution, prepared by dissolving 0.1247 g of $NH_4H_2PO_4$, 0.457 g of $NH_4NO_3$ and 0.288 g of KCl in 1000 ml of reverse osmosis water. Five seeds of FAO 270 hybrid corn were sown per pot, later thinned to four seedlings after germination. Each pot was weighed daily and ion-exchanged water supplied to maintain 60% of the maximum water holding capacity. Soil samples for Phospholipid Fatty Acid (PLFA) analysis were collected at 2, 12, 19, 40 and 61 days after pesticide application. The soil microbial biomass based on total PLFA and its community composition (saprophytic fungi, Gram-positive bacteria, Gram-negative bacteria, actinomycetes, arbuscular mycorrhizal fungi, fungi to bacteria ratio and Gram-positive to Gram-negative bacteria ratio) were determined. Data were analyzed using repeated measures ANOVA to assess the effects of pesticide treatment and time on soil microbial biomass and community composition in SPSS (version 29). Results indicate that pesticide treatments did not significantly differ in overall microbial biomass and community composition ($F(4,15) = 2.17$, $p = 0.123$, $\eta^2 = 0.366$). Time had a significant effect on microbial parameters (Pillai's Trace = 0.947, $F(4,12) = 53.27$, $p < 0.001$, Partial $\eta^2 = 0.947$), indicating that soil microbial biomass and community composition changed between sampling time points. The highest microbial biomass generally was observed at 61 days post pesticide application. No significant interaction of Time x Treatment (Pillai's Trace = 0.977, $F(16,60) = 1.21$, $p = 0.286$, $\eta^2 = 0.244$) was found, indicating that pesticide application did not influence how microbes changed over time. We attribute the microbial biomass at 61 days to the high root density, which increased exudates in the soil, hence boosting microbial life. In conclusion, treatments behaved similarly throughout the study period, with no pesticide underperforming or outperforming the others. Progress of growing season, rather than pesticides applied, was the determining factor responsible for changes in microbial groups.

**Key words:** PLFA analysis, soil microbial biomass, soil-applied pesticides, corn

# Developing a Framework for Soil Microbial Indicators

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**ABSTRACT**

Growers, advisers and policy makers are increasingly turning to soil biology to explain soil function, security and resilience, yet there is limited consensus on which microbial indicators to measure, how to interpret values, and how to link them to agronomic outcomes. Existing soil health frameworks typically focus on sets of chemical and physical indicators, with biological measures often added opportunistically and interpreted in isolation. This limits confidence in biological testing and constrains uptake of emerging microbial diagnostics for on-farm decision making.

A research program spanning a wide agro-climatic zone was established to develop and validate a framework for interpreting soil microbial indicators in broadacre grain systems under varied management practices. Five field experiments (cover cropping, herbicide withdrawal, alleviation of abiotic stress in calcareous soils, and regenerative versus conventional management) were monitored over two years. At each site, soils were sampled at key crop growth stages and characterized using a tiered indicator suite targeting: (1) microbial food sources, (2) microbial community structure, (3) potential microbial activity, (4) realized biological functions, and (5) agronomic and ecosystem outcomes.

The framework integrates this soil biological cycle by linking plant-derived carbon inputs and soil organic matter pools (e.g. total C/N, MIR-predicted C fractions, hot-water extractable C and N, soil C fractions, autoclave–citrate–extractable protein) with measures of "who is there" (amplicon sequencing of bacteria and fungi, qPCR quantification of agriculturally important populations, such as mycorrhizal fungi and nematodes). Potential and realized functions including soil enzyme activities, pathogen suppression, and N-cycling outcomes were also assessed and related to crop performance metrics, such as biomass and yield.

Multivariate and correlation-based analyses were used to identify linkages among indicators and to improve the interpretability and translation of meaningful biological indicators. The outcome is a scalable framework that has synthesized a wide array of biological measurements into interpretable metrics for decision-making. This framework has been translated into decision-support tools and training resources for researchers, service providers and landholders, enabling soil microbial testing to be integrated into soil health assessments across Australian grain production landscapes.

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# Effects of sustainable cropping systems on soil fauna and microbial biomass and aggregate structure

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**ABSTRACT**

Sustainable cropping systems, particularly no-tillage, are known to enhance soil biodiversity and physicochemical properties. Despite these benefits, their adoption and related research remain limited in Japan, which requires field-scale trials to support their expansion. This study aimed to investigate the effects of sustainable cropping systems on soil biological and physical properties and to clarify their interrelationships.

A five-year continuous soybean field experiment was conducted at Fukushima University, Japan, using 32 plots (8 treatments with 4 replicates) combining tillage (conventional tillage vs. no-tillage), weed management (herbicide vs. no-herbicide), and fertilizer (chemical vs. organic). In July 2024, earthworm populations were sampled using hand-sorting at 0–10 and 10–20 cm depths and mustard extraction at >20 cm depths. Soil microbial biomass carbon (MBC) and nitrogen (MBN) were determined using the chloroform fumigation-extraction method. Mean weight diameter (MWD) of aggregates was determined using the wet-sieving method. Both analyses were conducted on soil samples from 0–10 and 10–20 cm depths. The carbon content of each aggregate fraction was also measured.

No-tillage significantly increased earthworm population density, particularly of the Moniligastridae family, which is less commonly reported in Japan. MBC and MBN in the 0–10 cm soil layer showed the highest values under the combination of no-tillage, no-herbicide, and organic fertilizer treatments. Among the factors tested, no-tillage was the primary factor contributing to increased soil fauna and microbial biomass. No-tillage also improved MWD, indicating enhanced aggregate stability, which led to a higher proportion of macroaggregates and increased carbon content within macroaggregates. Path analysis showed that no-tillage promotes microbial biomass by developing soil aggregates, which provide crucial habitats.

These findings highlight the no-tillage production system as a key practice for improving soil biodiversity and health. Our results also suggest the potential for the wider adoption of sustainable cropping systems in Japanese agriculture.

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# Impact of long-term conservation agriculture on soil biota and inter-taxonomic interactions in Andisols, Japan

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## ABSTRACT

**[Background and Objective]**

Conservation agriculture (CA), combining no-tillage (NT) and cover crops (CC), is increasingly adopted for sustainable farming, yet its impacts on soil biota, particularly protists and nematodes, and their functional interactions remain insufficiently understood. We investigated soil biotic communities, trophic interactions, and functional attributes under long-term CA in humid Andosols, Japan.

**[Methods]**

The study site was the long-term experimental field (>20 yr) of Andisols in Ibaraki University, Japan. Surface (0–5 cm) and subsurface (5–15 cm) soils were collected from conventional tillage (CT) and NT under low and high CC densities across three seasons. Microbial abundance was quantified by digital PCR, and amplicon sequencing profiled bacteria, fungi, protozoa, and nematodes. Along with the measure of soil physicochemical and biological properties, β-glucosidase activity (BG) was measured, and microbial C metabolic efficiency was evaluated using BG normalized to microbial biomass C (BG/MBC). Linear mixed model was used to assess the effect of each factor on targeted properties. Community composition and multitrophic networks (SPIEC-EASI) assessed treatment and seasonal responses.

**[Results and Discussion]**

Long-term NT markedly increased SOC (12.8 g kg−1), MBC (~200 mg kg−1), soil moisture (~3.5 wt%), and available N (64.6 mg kg−1) in the surface soil, whereas CT maintained higher values in the subsurface. Across seasons, NT consistently doubled MBC and microbial DNA abundances for bacteria and fungi in the surface soils, while CC effects on soil properties were minimal. All treatments remained bacteria-dominated (fungi: bacteria < 0.05), and BG/MBC ratios were comparable, indicating similar microbial C metabolic efficiency. Community structure diverged strongly by tillage: CT bacterial communities shifted seasonally, whereas NT communities were more stable throughout the year. RDA and LEfSe associated higher SOC under NT with enriched Proteobacteria and Bacteroidota, which can support protozoan predation. Multitrophic networks integrating bacteria, fungi, protozoa, and nematodes revealed that NT topsoil supported a more highly connected soil food web, with ~1.2–1.8× more edges, higher mean connectivity, and greater representation of bacterial–protozoan interactions. NT networks also exhibited lower modularity, indicating a more integrated community structure. These findings suggest that NT, rather than CC management, fosters a more cohesive and dense-linked soil biotic network, potentially contributing to enhanced C cycling in NT topsoil.

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# Effects of five-year of conservation agriculture on soil chemistry and soil biological communities in Japan

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## ABSTRACT

**[Background and Objective]**

Conservation agriculture (CA), a combination of no-tillage and cover cropping, has attracted attention for its potential to achieve carbon sequestration and enhance soil biological properties. The effects of CA have been investigated mainly under long-term management (>10 years), and it is known that longer durations tend to result in clearer changes in both soil physicochemical and biological properties. To examine the short-term effects of CA, this study aimed to evaluate how five years of CA influence soil chemical properties and biological communities in a Japanese agricultural field.

**[Methods]**

The study site was the Masuzawa Field in Fukushima University, a former paddy field where CA has been implemented for five years. This site has a temperate climate, and the soils are classified as Inceptisols (brown forest soil). Soil samples were collected from four soybean cultivation plots combining two treatments—tillage vs. no-tillage and presence vs. absence of weed residues (+weed vs. -weed). Sampling was conducted in June 2024 (just after sowing) and November 2024 (just before harvest) from two soil layers (0–5 cm and 5–15 cm), with four field replications per treatment. In addition to soil chemical properties (e.g., total soil carbon), biological properties were measured. Microbial abundance (bacteria and fungi) was quantified using dPCR. β-glucosidase activity was measured as a representative enzyme activity. Biological community composition and cross-kingdom interaction networks among bacteria, fungi, protists, and nematodes were analyzed using amplicon sequencing.

**[Results and Discussion]**

Total carbon content was higher only in the surface (0–5 cm) soil of no-tillage plots compared with tillage plots (–weed: +28%, +weed: +39%), confirming the effects of no-tillage and additional weed residues on carbon accumulation in surface layers where plant residues accumulate. Regardless of sampling times, bacterial and fungal DNA copy numbers were 2.0–3.0 times higher in the surface layer under no-tillage than in tillage plots. β-glucosidase activity was also 2.3–3.0 times higher in the surface layer. These comparable increases suggest that microbial abundance may directly contribute to elevated soil enzyme activity. As for biological communities, clear no-tillage effects were observed for bacteria, fungi, and protists (but not for nematodes). In bacteria, significant increases were detected in *Bacteroidota* and *Proteobacteria*, which are often associated with r-strategists. In contrast, the weed treatment did not lead to clear changes in community composition. Network analysis revealed that bacteria-centered biological networks were strengthened in the subsurface layer of the no-tillage plots, but not in the surface layer. As the subsurface network was composed mainly of paddy-oriented biota, these effects of CA on the subsurface layer might be specific to former paddy fields. Overall, even after five years of management, CA led to increased soil carbon, higher microbial abundance, and community shifts in the surface layer, and furthermore strengthened biological networks in the subsurface.

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# Effects of Acai Seed Biochar Amendment on Chemical and Biological Properties of Brazilian Soils

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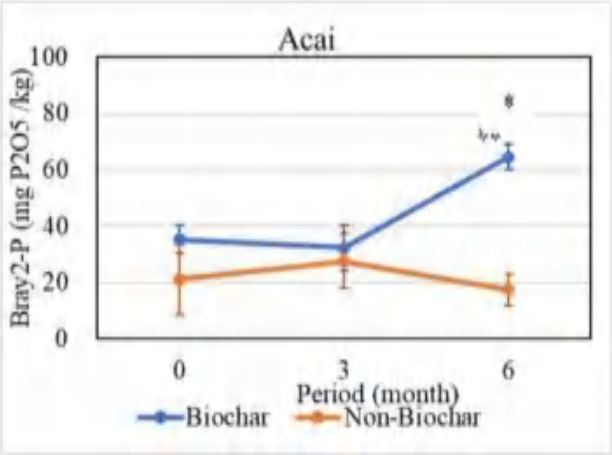
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## ABSTRACT

Biochar derived from acai (*Euterpe oleracea*) seeds offers a sustainable option to valorize acai production residues, which otherwise accumulate in high volumes and contribute to fungal disease proliferation in field disposal. We hypothesized that amending soils with acai-seed biochar can enhance soil carbon (C) sequestration, improve phosphorus (P) availability through enhanced P-solubilizing microbial activity, and shift the soil microbial community toward beneficial taxa. To test these hypotheses, we conducted a controlled incubation experiment using soils representative of major Brazilian biomes (Amazon — acai-cultivated and native, Cerrado, Atlantic Forest, Semi-arid Caatinga), with and without 10% (w/w) acai biochar addition. Soils (250 g) were incubated in the dark at 25 °C for six months, with sampling at 0, 3, and 6 months. Chemical analyses included total and available P, amorphous Fe and Al, total C and N, C/N ratio, and pH. Biological analyses comprised the bacterial and fungal community profiling via metagenomic sequencing. Biochar amendment significantly increased available P — particularly in Amazon and Cerrado soils — and enhanced total C and the C/N ratio across all soils. Metagenomic data revealed an increased relative abundance of beneficial fungal genus (e.g., *Trichoderma*) in Amazon Native and Acai soils amended with biochar after three- and six- months incubation. There was positive correlation between this fungal genus and available P, even though statistically non-significant. These findings can support that acai-seed biochar improves soil fertility and some fungal groups more locally and individually than at general scale.

**Keywords:** biochar; acai seed; soil carbon; phosphorus availability; soil microbiome

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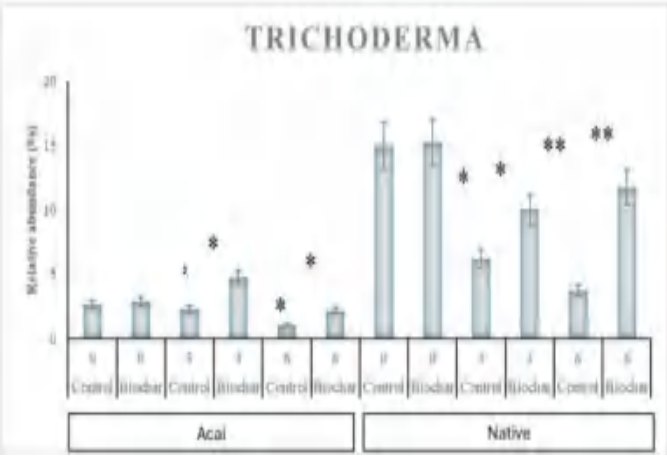




Fig. 1 – Available phosphorus in Acai soils with and without Biochar (*,** Significant at 95 and 99% by Tukey test within each month).

Fig. 2 – Relative abundance of *Trichoderma* in Acai and Native soils with and without Biochar (*,** Significant at 95 and 99% by Tukey test within each month).

# Overlooked migration risk of resistomes in mining soil environments

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**ABSTRACT**

Global mining activities have impacted vast downstream regions through heavy metal accumulation, significantly altering soil microbial communities and enriching antibiotic resistance genes (ARGs) via co-selection with metal resistance genes. Mining environments have been recognized as important reservoirs of ARGs, yet their potential migration into surrounding ecosystems and associated risks remain poorly understood.

Here, we conducted a national-scale investigation, analyzing 416 soil metagenomes to comprehensively characterize the mining resistome and its migration potential. We found that mining soils were enriched in bacitracin resistance genes. Host analysis revealed that 60% of ARG-carrying genomes (ACGs) detected in downstream farmland were shared with those from mining sites. Source tracking indicated that 57% of quinolone resistance genes in farmlands likely originated from mining areas. Bipartite network analysis additionally supported the potential migration of resistomes from mining sites to farmlands. Using an optimized risk assessment framework, we identified 14 high-risk mining ARGs, half of which had not been reported previously. These high-risk ARGs exhibited distinct geographic distributions between southern and northern regions, and many of their hosts remain uncharacterized.

To our knowledge, this study provided the first systematic, national-scale evidence of ARG dissemination potential from mining environments into agricultural ecosystems. By identifying previously overlooked high-risk ARGs, this research addressed critical knowledge gaps in evaluating resistomes from extreme environments and offered essential insights for managing ARG migration risks.

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# Temporal and Specific Effects of Micronutrient Addition on Soil Microbial Communities in Desert Steppe

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**ABSTRACT**

Nutrient inputs are continuously altering desert steppe ecosystems; however, micronutrients—acting as key drivers of aboveground productivity and central mediators of belowground microbial community responses—have been relatively understudied in terms of their roles in shaping soil ecological processes in desert steppe. Therefore, we conducted a laboratory incubation experiment to investigate the effects of micronutrient (Mg, Fe, Mn, Cu, $ZnCl_2$, $ZnSO_4$) addition on the soil microbial community of a desert steppe under different incubation durations. The results showed that: (1) micronutrients exerted element-specific inhibitory effects on soil microbial diversity, with Mg, Fe, and Cu significantly reducing bacterial diversity, while Mn caused a persistent suppression of fungal diversity ($P < 0.05$); (2) microbial community responses to micronutrient additions displayed clear temporal dynamics. Although the overall succession followed a transition from r- to K-strategist communities, specific elements were able to regulate the intrinsic strategies of certain taxa. In particular, the addition of Mg or Fe delayed the response of typical r-strategist phyla (e.g., Proteobacteria), while inducing an earlier response of some K-strategist phyla (e.g., Acidobacteriota); and (3) redundancy analysis (RDA) indicated that specific micronutrients (e.g., Mg, Cu, and Zn) and the C:P ratio were key environmental factors driving fungal community succession, with their effects being time-dependent. During the early incubation stage (15 days), fungal communities were mainly driven by Mg and the C/P ratio, whereas during the later stage (90 days), Cu and Zn became the dominant drivers. Our results reveal that micronutrients play a decisive role in regulating soil microbial communities in desert steppe, providing critical theoretical support for improving nutrient management strategies and for enhancing ecosystem resistance to disturbance and the maintenance of ecosystem stability.

**Keywords:** Desert steppe; Micronutrients; Soil microbial diversity; Soil microbial community structure; Ecological strategy.

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# 3D Structure of Ground-nesting Bee Burrows under Fertilization Treatments in Black Soil Areas: A Study Based on X-ray CT

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**ABSTRACT**

Fertilization significantly alters soil physical and chemical properties, thereby indirectly affecting the nesting behavior and three-dimensional architecture of ground-nesting bees, yet the specific mechanisms remain unclear. This study investigated the responses of soil properties and the 3D burrow architecture of ground-nesting bees to long-term fertilization in the black soil region of Jilin, China. Using X-ray computed tomography (XRCT), we compared three treatments: no fertilizer (CK), conventional mineral fertilization (NPK), and integrated organic–inorganic fertilization (NPK+M).

Key findings indicate: (1) Fertilization significantly modified the topsoil (0-10 cm) environment, with both NPK and NPK+M treatments significantly reducing soil pH and increasing available phosphorus content and penetration resistance, while effects on bulk density, volumetric water content, and available potassium were not significant. (2) Fertilization selectively influenced burrow architecture. Both fertilized treatments significantly increased burrow depth (NPK: 26.31 cm; NPK+M: 26.58 cm) but reduced burrow abundance, particularly under NPK+M. NPK significantly increased the maximum burrow diameter, an effect not observed under NPK+M. Fertilization did not significantly affect average diameter, volume, or branch number, although the highest values for volume and branch number were recorded under NPK+M. (3) Soil layer-specific correlations were identified. In the 0-5 cm layer, available phosphorus and penetration resistance were negatively correlated with burrow abundance. In the 5-20 cm layer, bulk density positively correlated with burrow depth. In the deep layer (20-30 cm), bulk density, water content, and penetration resistance all positively correlated with burrow depth but negatively with burrow abundance. Burrow volume and branch number were strongly positively correlated across all layers.

This study demonstrates that fertilization does not directly alter the inherent structural characteristics of bee burrows, such as average diameter. Instead, it modifies soil acidity, nutrient availability, and physical compactness—particularly the penetration resistance of topsoil, thereby influencing the selection of nesting sites, including depth and abundance, as well as certain morphological traits like maximum diameter. Under the organic-inorganic combined fertilization treatment, a trade-off was observed: the structural complexity of individual burrows increased, while the nesting population declined. This suggests a potential balance between soil resource availability and habitat suitability. These findings provide important evidence for understanding how agricultural management practices, particularly fertilization strategies within conservation tillage systems, influence agricultural ecosystem functions through soil biological engineering pathways.

**Keywords:** Ground-nesting bee burrows; X-ray CT; Black soil; Fertilization management.

Minghan Liu, Author, 3D Structure of Ground-nesting Bee Burrows under Fertilization Treatments in Black Soil Areas: A Study Based on X-ray CT.

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# Ecological strategies govern fungal performance on soil carbon cycling in agroecosystems

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**ABSTRACT**

Fungi are pivotal to soil health, however, how do fungal types with different ecological strategies mediate soil functioning remains poorly understood. The responses of fungal ecotypes, defined by their adaptation as specialists, opportunists, or generalists in shaping community structure and function were illustrated through long-term (>10 years) nitrogen (N) gradient experiment across four regions with contrasting soil fertility. The results showed that overall fungal abundance increased with increasing soil fertility, while alpha diversity declined and the ecological niche of fungi narrowed. Critically, specialists and opportunists exhibited different performances in community, namely the relative abundance of specialists increased whereas that of opportunists decreased with increasing soil fertility. Specialists characterized by high energy metabolism and respiration became enriched in high-fertility soils, favoring the dominance of saprotrophic fungi following N addition. Such community shift drives functionality alteration, e.g., the diversity of carbohydrate metabolism and the capacity for cellulose degradation increased. A key specialist, *Mortierella elongata*, became dominant in high-fertility soils. In contrast, opportunists were suppressed by specialists in high-fertility soils, promoted pathogen abundance via decomposing amino acid rather than intervening degrading cellulose in low-fertility soils, especially under N enrichment. By comparison, generalist with low abundances remains stable across all soils. Collectively, organic carbon dynamics and eventually soil fertility were changed by fungi with different ecological strategies, advancing mechanistic understanding of how fungi communities maintain and modulate soil fertility.

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# Effects of compost application on rhizosphere microbial communities of wheat grown in sandy soil under different tillage practices

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**ABSTRACT**

Sandy soil is typified by loose structure, poor aggregation, low organic carbon content, and limited nutrient and water-holding capacities. Organic compost application represents an effective ameliorative strategy for this kind of soil, with its effects interacting with tillage practices. Nevertheless, studies examining these interactions remain relatively limited in sandy soil ecosystems in Chiping District, Liaocheng City, Shandong Province. This study investigated the effects of compost application under three tillage practices—subsoiling (SS),deep ploughing (DP),and rotary tillage (RT) on the composition and structure of bacterial and fungal communities in the soil. The results insight for targeted sandy soil improvement and sustainable farm management.

Compost application, in combination with tillage, modified the community composition of both bacteria and fungi across soil layers. In the 0–20 cm layer, compost-amended treatments significantly increased the abundance of the bacterial phylum Gemmatimonadota while reducing the relative abundances of the bacterial phyla Pseudomonadota and Chloroflexi and the fungal phylum Basidiomycota. In the 20–40 cm layer, compost addition similarly enriched the bacterial phylum Gemmatimonadota and the fungal phylum Ascomycota. Moreover, compost application together with tillage practices noticeably affected the alpha diversity of both soil bacterial and fungal communities.

**Acknowledgments**

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# Dung-applied anthelmintic drug Moxidectin alters free-living soil nematode communities

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**ABSTRACT**

Anthelmintics, such as moxidectin (MOX), are widely used to treat or prevent gastrointestinal parasites in livestock and companion animals. Up to 77% of the dose applied to animals is excreted via feces and can ultimately enter the soil environment either through grazing animals or application of manure. Based on its wide application and potential ecotoxic effects the impact of anthelmintic drugs on non-target organisms has been widely studied and there is evidence for negative effects on seed germination and dung dwelling fauna. However, effects on free-living nematodes, an organism group with soil food web interactions at every trophic level and great ecological importance are insufficiently addressed with a focus on quantitative measurements. We established a pot experiment to compare nematode communities in soils with 0.25, 0,5 or 1 mg MOX with control soils in five replicates respectively. Nematodes were counted and identified to genus level. Additionally, microbial biomass carbon (MBC) and soil nitrogen were measured to identify possible interactions of nematode abundances with resource availability and soil functioning. Nematode indices were used as indicators of soil disturbance. Similar to previous studies overall nematode abundance was not affected by anthelmintics. However, the community composition was altered with a decrease in c-p3 (colonizer-persister) nematodes, which are characterized by longer life cycles and greater sensitivity to disturbance. Opportunistic nematodes with faster reproduction rates and greater disturbance tolerance (≤c-p2) dominated the communities with MOX and correlated with MBC. A decreased Maturity 2-5 index and Structure index indicate a toxic disturbance by MOX. The genus richness of the communities was not affected but the evenness was reduced with 0.25 and 0.5 mg MOX compared to controls. While soil mineral N was not affected, we found that total N was reduced with MOX suggesting changes in soil N mineralization. Our results show that quantitative measurements alone are not sufficient to assess the effects of medical compounds entering the soil environment but rather the focus should be on qualitative measurements that capture potential species loss and associated changes in ecological functioning of the soil communities.

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# Soil Carbon Trend Index (SCTI): A Biochemical Tool for Predicting Carbon Dynamics in Agricultural Soils

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**ABSTRACT**

A growing body of evidence suggests that soil organic carbon (SOC) and enzymatic activity exhibit biochemical equilibrium in natural and long-term managed systems. Building on this principle, the Soil Carbon Trend Index (SCTI) was developed as part of the BioAS technology to assess the trajectory of SOC in response to land use and management changes. The SCTI compares the enzymatic sufficiency level—based on the activity of arylsulfatase (ARIL) and β-glucosidase (GLI)—with the SOC content, both normalized using texture-specific scoring curves for Brazilian Cerrado Oxisols. The index ranges from –1 to +1, where values below zero indicate a tendency for SOC loss, values above zero indicate SOC accumulation, and values near zero reflect biochemical equilibrium. The SCTI was tested in a long-term field experiment (2008–2024) in Itiquira, Mato Grosso (Brazil), evaluating the transition from conventional soybean monoculture to no-till with soybean–brachiaria rotation. Between 2016 and 2020, under conventional management, ARIL and GLI levels were 18 and 32 µg $pNP.g^{-1}.h^{-1}$, respectively, with SOC at 15.5 $g.dm^{-3}$ and an average SCTI of –0.15. Following adoption of conservation practices in 2020, ARIL and GLI rose to 68 and 182 µg $pNP.g^{-1}.h^{-1}$, while SOC increased to 17.4 $g.dm^{-3}$ by 2024. The SCTI shifted to 0.14 in 2022 and 0.17 in 2024, capturing the shift toward carbon accumulation. These results confirm the sensitivity of enzyme activity to management changes and the SCTI's ability to anticipate SOC trends. Ongoing research aims to relate SCTI values not only to the direction of change, but also to the magnitude and rate of SOC variation across soil types and land use systems. The SCTI offers a promising, low-cost biochemical indicator for regional soil health monitoring and carbon reporting.

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# Assessment of the Stabilizing Effect of Compost and Phosphogypsum on the Metabolism of Bacillus subtilis and Pseudomonas putida in Sod-Podzolic Soil Contaminated with Lead and Zinc

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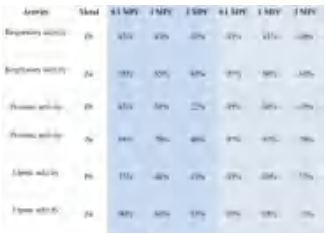
**ABSTRACT**

The work summarizes data from laboratory experiments on the inhibitory effect of Pb and Zn (0.1; 1; 2 MPC. Pb - 32 mg/kg, Zn - 23 mg/kg) on the metabolic activity of Bacillus subtilis and Pseudomonas putida in anthropogenically degraded sod-podzolic soil, with an assessment of the stabilizing effect of compost from quail manure and phosphogypsum. A dose-dependent suppression of respiratory, protease, and lipase activity was established. Compost and phosphogypsum reduce toxicity, increasing the activity of microorganisms, confirming their potential for bioindication of heavy metal pollution. The specified metals inhibit key enzymatic and respiratory processes in microorganisms (Bacillus subtilis and Pseudomonas putida), which play an important role in the degradation of organic substances. The application of organic ameliorants, such as compost from quail manure and phosphogypsum, promotes the immobilization of metals and stimulation of microbial activity (Tab.1).

The aim of the study was to analyze the inhibitory effect of increasing concentrations of Pb and Zn on the metabolic activity of Bacillus subtilis and Pseudomonas putida in anthropogenically degraded sod-podzolic soil with an assessment of the stabilizing effect of compost and phosphogypsum. A dose-dependent inhibition was observed.

**Key words:** *BACILLUS SUBTILIS* (L),*PSEUDOMONAS PUTIDA* (L), LEAD, ZINC, MICROBIAL BREATHING, BIOINDICATION.

**Table 1:** metabolic activity of Bacillus subtilis and Pseudomonas putida without ameliorants (% of control)



With the use of ameliorants, a stabilizing effect was observed, reducing inhibition. (Tables 2-3)

**Table 2:** metabolic activity of Bacillus subtilis and Pseudomonas putida with compost (% of control)

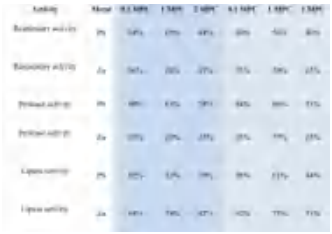
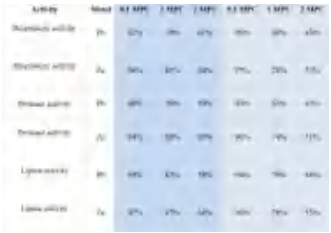


**Table 3:** metabolic activity of Bacillus subtilis and Pseudomonas putida with phosphogypsum (% of control)



Conclusions: Pb/Zn suppress metabolism in a dose-dependent manner. Ameliorants stabilize the metabolism of microbiota, reducing inhibition.

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# Locally Conserved Microbial Signatures as Global Indicators of Plant Productivity

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**ABSTRACT**

Soil biodiversity underpins key ecosystem functions, yet its potential to serve as a scalable indicator of soil health and plant productivity remains underexplored. In this study, we investigated whether fine-scale microbial patterns associated with yield within a single agricultural field can be generalized to predict plant growth across global ecosystems. High-resolution soil sampling was conducted on a maize field in Germany, coupling 16S rRNA sequencing with spatially explicit yield measurements. Using machine learning (LASSO regression), we identified a set of 26 bacterial genera whose abundances explained ~65% of local yield variation through cross-validation. These genera represent diverse taxonomic groups and include consistently yield-associating taxa such as Hyphomicrobium, Reyranella, Luedemannella, Aeromicrobium, Flavitalea, and Ellin6055.

To test the robustness and scalability of these local microbial indicators, we validated the model across seven independent, globally distributed datasets encompassing croplands, grasslands, and pastures. Despite differences in environmental conditions, sequencing methods, and productivity metrics (yield, soil health indices, and NDVI-based net primary production), the locally trained model successfully predicted up to 37% of global vegetation variation. Most of the key genera displayed coherent associations with productivity across continents, demonstrating that certain soil bacterial signatures respond predictably to plant growth independent of biome, climate, or pH gradients. Additional analyses controlling for major climatic variables showed that these associations persist beyond broad environmental drivers, suggesting that microbial traits linked to resource turnover, carbon cycling, or plant–microbe feedback may be intrinsically tied to ecosystem productivity.

These findings provide evidence for a globally conserved set of soil bacterial indicators that capture meaningful variation in plant growth and soil function. They highlight the potential of microbiome-based modelling as a powerful tool for high-resolution soil health assessment, capable of integrating biodiversity metrics with agronomic and ecological outcomes. By bridging local microbial processes with global patterns, this work advances efforts to develop mechanistic, scalable, and biologically grounded indicators for sustainable soil management.

# Predatory protists – crucial drivers of soil antibiotic resistance

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**ABSTRACT**

Unravelling the antibiotic resistance in nature is crucial for predicting and mitigating its worldwide impacts amidst rapid global change. While biological factors are considered as crucial drivers of ecological processes. However, their roles in driving the evolution of antibiotic resistance, a global health concern, remain poorly understood in complex natural soil ecosystems. Whereas predatory protists and predatory bacteria are primary predators of bacteria, we have poor understanding about mechanisms underlying the influence of the bacterivorous predators on bacterial antibiotic resistance within a multitrophic soil ecosystem. Here, through quantitative PCR and amplicon sequencing, we assessed effects of soil predatory protists on predatory bacteria and antibiotic resistance genes (ARGs) across a gradient of protist concentrations under the control of bacteria's competitors – fungi. Our findings reveal that high-protist predation significantly increased the relative abundance of dominant predatory bacteria between days 15 and 45 of the microcosm incubation. Aligning with a rising abundance of predatory bacteria and antibiotic-producing bacteria, the relative abundance and diversity of soil ARGs significantly increased under high protist concentrations, regardless of fungal effects. Many ARGs encoding key antibiotic deactivation and efflux pumps were enriched in response to predatory protists within complex inter-group interactions. Moreover, these enriched ARGs were strongly associated with both predatory bacteria and predatory protists. More profound effects of predatory protists on predatory bacteria and soil ARGs were identified in the presence of fungi. Our study provides novel evidence about crucial effects of predatory protists on shaping the predatory bacterial community and driving bacterial antibiotic resistance under complex multitrophic interactions in a natural soil. These findings pave the way for future research aimed at mitigating this global health issue and uncovering other ecological processes.

**Acknowledgments**

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# Soil Health Under Climate Change Era: Restoration Strategies using Nanobiotechnology and Soil Engineering

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**ABSTRACT**

Past few decades, due to intensive agriculture cultivation, the soils are getting huge amount of chemical-based fertilizers/pesticides, which is directly/indirectly affecting the soil microbiota; especially rhizospheric microbiome. These soil microbes are playing significant role to help plants to uptake nutrient, make unavailable elements to available form, and responsible for decomposition to enhance soil fertility. Soils are not only suffering with agro-chemical inputs, but it also facing various abiotic-abiotic stresses, including heavy metals and emerging contaminates accumulation such as nanoparticles, microplastics, pharmaceuticals and personal care products. The organic matter is continuously decreasing, and soil are losing its fertility and productivity. Due to the population explosion under this climate change era, to achieve the "Zero Hunger" goal in sustainable way is a challenging issue. It is necessary to solve the fundamental tasks that are of frontier importance for soil science today. The recent research developments, and combination of various emerging technologies such as nanotechnology, carbon or biochar materials, genomic, synchrotron, neutron, microbiome and metabolome, and genome editing tools open new avenue to restore soil health via soil engineering; especially rhizospheric microbiome. Thus, our focus on research is to edit soil rhizospheric microbiome and study its responses, determine dynamics, nature and features of interactions in the soil-microbe-plants system. To analysis of the processes occurring in rhizosphere in presence of nanoparticles, nanofertilizers and nanocarbon materials using synchrotron-neutron methods and NBIC (Nano-, Bio-, Information, and Cognitive) technologies to improve the soil fertility, to restore degraded soils, artificial soil system. Analyzed the processes and mechanisms of interphase interactions between the surface of soil particles, plant roots and microbes with the participation of nanoparticles. The structure and functions of the rhizosphere, and the possibilities for optimize its condition is critical to design the artificial ecosystem. Thus, the advanced technologies that is capable to decode the biological and ecological processes, and interactions in rhizosphere system were used such as genomic, synchrotron, neutron tomography methods and computer modeling with microscopic methods. The neutron computed tomography helped to construct a 3D combined image ofthe rhizosphere structure at the micro-level, whereas, omics technologies characterized the microbiome and metabolome ofthe rhizosphere.

**Keywords:** Soil Health, Bioengineering, Plant Growth, Climate Change, Microbial Community

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# Dynamics of Native Low Molecular Weight Organic Substances (LMWOS) and Their Relationship to Soil Quality Indices in Gray Lowland Soil

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**ABSTRACT**

Low molecular weight organic substances (LMWOS) specifically carbohydrates, organic acids (OAs), and amino acids (AAs) in an agricultural soil system are recognized as integral components of soils together with inorganic constituents. However, their fundamental dynamics remain poorly understood. Although numerous studies have reported that LMWOS influence crop growth, systematic evaluations of their dynamics and storage characteristics in soils from the perspective of sustainable soil fertility management are still limited.

In this study, we investigated changes in LMWOS dynamics induced by rewetting and their relationships with soil microbial communities and soil quality indices. Gray lowland soil, a widely used agricultural soil type was air-dried, debris removed and subjected to a controlled rewetting process by adjusting the moisture content to 60% of the maximum water holding capacity (WHC). The sample were then incubated at 27°C to monitor the basal fluctuations of organic LMWOS at specific time intervals. To track these native LMWOS, Gas Chromatography-Mass Spectrometry (GC-MS) was employed to analyze water-extractable carbohydrates, OAs, and AAs.

The results of the 14-day incubation revealed that the LMWOS dynamics varied significantly over time, with particularly rapid changes in carbohydrate and OAs concentrations occurring within the first few days after the onset of incubation. To further evaluate the relationship between these LMWOS dynamics and soil health, quality indices were quantified using standard laboratory protocols: pH was measured in a soil-water suspension; total carbon (TC), total organic carbon (TOC), and total nitrogen (TN) were determined using an elemental analyzer; free $NH_4^+$ was analyzed following soil extraction; and microbial biomass carbon (MBC) was measured via the fumigation-extraction method. In addition, next-generation sequencing (NGS) analysis of soil microbial communities is currently underway. This integrated approach provides a mechanistic basis for understanding soil fertility regulation under fluctuating moisture conditions.

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# Comparison of different methods for estimating microbial biomass in biochar-amended soils

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**ABSTRACT**

Biochar use as a soil amendment can improve soil functions, enhances microbial activity, and increases crop production. However, due to its high sorptive capacity, it may interfere with traditional methods for determining soil microbial biomass, specifically chloroform fumigation-incubation (FI) and fumigation-extraction (FE). This study aimed to assess the impact of biochar on microbial biomass determination using traditional methods and a new $CO_2$ high pressurization (CO2HP) technique. Five treatments were set up: unamended soil (control), and soil amended with two types of biochar, produced at 440 °C (B440) or 880 °C (B880), at two application rates (20 or 40 t $ha^{-1}$). Following cell lysis by fumigation or CO2HP, released microbial C ($\Delta C_{mic}$) was estimated by determining microbial respiration over a 10-d incubation (FI and CO2HP-I methods, respectively) or by extracting soluble organic C (FE, and CO2HP-E, respectively), while released microbial N ($\Delta N_{mic}$) was estimated by determining extractable total N exclusively by FE and CO2HP-E methods.

Without biochar, $\Delta C_{mic}$ estimates were similar across FE, FI, and CO2HP-E methods. Contrarily, CO2HP-I method greatly overestimated $\Delta C_{mic}$ compared to the other three methods, particularly at the higher biochar rate, suggesting that the adsorption of $CO_2$ within biochar pores during CO2HP treatment and subsequent slow release during incubation could have produced artifacts. The presence of B880 resulted in a decrease in $\Delta C_{mic}$ values, which might have been caused by an acclimation of microbial biomass to new habitat. Contrarily, the addition of B440, increased $\Delta C_{mic}$ when determined by the FE method, compared to FI and CO2HP-E methods. This suggested an overestimation of extractable C after fumigation, possibly due to adsorption of $CHCl_3$ by the B440 biochar, rich in functional groups, that might have bound $CHCl_3$. We concluded that biochar interfered with the determination of $\Delta C_{mic}$and $\Delta N_{mic}$ as a function of both type and amount added.

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# Species-Specific Effects of Earthworm on Soil Modification Functions Across an Ecosystem Development Gradient: Evidence from Miyakejima and Mikurajima, Japan

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**ABSTRACT**

Earthworms are widely recognized as "ecosystem engineers" due to their crucial roles in organic matter decomposition, soil structure formation, and nutrient cycling. Earthworm casts impact the soil environment through aggregate formation, thereby enhancing water retention, stimulating microbial activity, facilitating nitrogen mineralization, and carbon storage. Previous studies have shown that presence of earthworms promotes soil aggregate formation, increases organic carbon and nitrogen contents, and enhances soil enzyme activity and microbial diversity. However, most studies have focused on single species or treated earthworms as a functional group, with few examining how species-specific differences influence soil functions. Comparative studies focusing on earthworm species distributed in Japan are still limited, leaving many aspects unexplored. This study aims to clarify species-specific differences in earthworm effects on soil modification functions by examining multiple species.

Miyakejima and Mikurajima, which represent different stages of ecosystem development, were selected as study sites for the rearing experiments. Collected earthworm individuals were reared individually for two weeks under controlled conditions using soil from their native habitats. After the rearing period, species identification was conducted based on morphological observation, and DNA analysis performed by an external laboratory. Soils containing earthworm casts were collected and analyzed for total nitrogen and organic carbon content, exchangeable cation, and water-stable aggregate to evaluate the physicochemical properties of the soil. In addition, three-dimensional visualization of cast internal structure was conducted using micro-X-ray computed tomography, enabling non-destructive analysis of the pore structure and the spatial distribution of organic matter and minerals in soil aggregates collected at earthworm sampling sites.

Results showed that total nitrogen content was higher in soils influenced by earthworm individuals collected from Miyakejima and Mikurajima compared to the control. While total organic carbon content did not increase uniformly across individuals, several individuals exhibited higher values than the control. Water-stable aggregate analysis revealed that for earthworms collected from both Miyakejima and Mikurajima, the proportion of aggregates smaller than 2 mm increased after rearing experiment compared to the control, while the proportion of aggregates between 0.25 and 0.5 mm decreased. Although body size is considered to influence soil modification functions to some extent, the results of this study suggested that other factors, including species-specific differences also play an important role.

In summary, by integrating soil biological, chemical, and physical analysis of soil properties, this study provides a comprehensive evaluation of species-specific earthworm-driven soil modification mechanisms.

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# The response of soil faunal and biological activities to silvicultural management in a Tuber Magnatum Pico productive area in Tuscany, Italy

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## ABSTRACT

In this study, we conducted a pedological and ecological assessment of a *Tuber Magnatum Pico* (i.e., white truffle) productive area where silvicultural management activities have been carried out, to track the response of the soil community. The aim was to identify biological proxies for soil health monitoring in white truffle productive areas, in addition to production itself.

The most frequent tree species in the area of interest, white and black poplars, have been subject to a succession of silvicultural interventions carried out in 2000, 2018, 2020, and 2021. In October 2021, three months after the last silvicultural intervention, a soil survey was conducted. Four homogeneous-management plots were identified along the river section where the area of interest is located. Two soil pits were described and classified as Calcaric Fluvic Cambisols with two different hydromorphic phases. Five sampling points were defined at each plot. We determined the soil parameters such as soluble carbon and nitrogen, organic matter, and carbonates; the soil microarthropod community, the microbial biomass using the dsDNA technique, and enzymatic activities such as arylsulphatase, β-glucosidase, chitinase, leucine, acid and alkaline phosphatases, bis-phosphatase, and inorganic pyrophosphatase. Multivariate linear modelling, together with comparative community analyses, was applied to the soil biological dataset. An effect of the silvicultural management was identified across the four plots. The plot where the most recent intervention was performed always showed higher rates of biological activity in all the biogeochemical cycles considered (i.e., C, N, S, and P). Overall, microbial biomass and P-cycle-related enzymatic activities were strongly associated. The plot intervened in 2020 showed the lowest soil biological activity, as well as the most unbalanced microarthropod community composition (i.e., taxa presence vs. taxa abundance), which is related to disturbed environments, as supported by scientific literature. In addition, truffles release substances that inhibit vegetation development; they can also affect the development of soil communities. In fact, when considering soil biogeochemical variables instead of soil properties when performing constrained correspondence analysis (CCA) on the microarthropod community, most of the 50% of the total variance is accounted for by the first two ordination components. This is proof of the high importance of trophic interconnections and ecological relationships shaping biological communities within the soil. Moreover, fungivorous taxa were more frequently found in samples from unbalanced communities and in higher-productivity plots. Similarly, predators were almost absent across all communities, which is associated with ecosystem imbalances. Finally, a strong relationship between the microarthropod community, arylsulphatase, and pyrophosphatase was identified.

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# Optimizing Methods for Selective Removal of Soil Nematodes to Study Their Functional Roles: Toward Effective Techniques with Minimal Impact on Soil and Plants

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## ABSTRACT

Soil nematodes play key roles in various soil processes, such as carbon and nutrient cycling, and the regulation of microbial activities. Their effects are often studied by comparing sterilized soils (nematode-free) with soils reinoculated with nematodes in microcosms, although these approaches frequently introduce unintended effects on soil properties, microbial communities, and plants, complicating causal inference and effect size estimation. An optimal partial sterilization method should selectively remove nematodes while minimizing unwanted side effects, yet systematic evaluations of the efficiency and side effects of commonly used methods remain limited. This study evaluated the effectiveness of dry heat, microwaving, freeze-thaw cycles, and gamma irradiation for selective nematode removal. Our results show that only freeze-thaw cycles (-80 °C to 22 °C, 72 h each) and microwave irradiation (135 s, 800 W) were highly effective for a sandy loam soil (700 g 1.4 g/cm$^3$, 50% water filled pore space), reducing nematode abundances in bare soil after two weeks and in planted soil after eight weeks to levels statistically indistinguishable from zero. The repeatability and side effects on soil physicochemical and microbiological properties of these two methods were then tested in soils with light (loamy sand) and heavy (silt loam) textures, compared to complete sterilization by autoclaving and an unsterilized control. No nematodes were detected in the microwaving and autoclaving treatments after six weeks of incubation, while 0.2% and 2.0% of the free-living nematodes observed in the control persisted in the freeze-thaw treatment in loamy sand and silt loam soils, respectively. Freeze-thaw and microwaving caused milder alterations to soil physicochemical properties than autoclaving. Leaching and soil powder inoculation significantly mitigated the increased mineral nitrogen content and suppressed microbial biomass carbon in all sterilized treatments, while enzymatic activities remained unaffected. Finally, a germination assay with *Lactuca sativa* assessing phytotoxic effects of these treatments on seedling emergence and early growth showed that the microwaving treatment resulted in similar seedling emergence compared to the control in both loamy sand and silt loam soils, while the autoclaving treatment showed only 47% or no germination in loamy sand and slit loam soils. In conclusion, microwaving emerged as the most promising technique, achieving complete nematode removal while minimizing adverse side effects, offering a practical tool for studying the functional roles of soil nematodes.

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# A Functional Molecular Framework for Scalable Soil Health Assessment

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**ABSTRACT**

Soil health is a multidimensional concept rooted in the integrated functioning of biological, chemical, and physical processes. However, current assessment frameworks often underrepresent the biological dimension, frequently relying on proxy measures that lack functional specificity. We propose a diagnostic approach that elevates biological indicators to the same analytical depth as physicochemical attributes, utilizing high-throughput molecular tools to directly decode soil microbial functionality. We developed a scalable soil health panel that unifies multi-proxy data within a function-oriented framework. This methodology enables the direct quantification of biological processes central to soil ecosystem services, such as nutrient cycling, carbon stabilization, and plant-microbe interactions. Biological data are derived from high-throughput omic techniques, where functional genes are curated and mapped to ecosystem-relevant categories: carbon and nitrogen dynamics, phosphorus mobilization, sulfur cycling, and stress-response mechanisms. A key innovation is the operational scalability and organizational workflow of the framework. By automating pipelines and increasing throughput, we significantly reduced per-sample costs and enhanced reproducibility. This optimization democratizes access to advanced molecular diagnostics, making the tool viable for both landscape-scale revegetation projects and smallholder farmers. The panel is currently deployed across diverse contexts, including large-scale restoration programs (500,000 ha), land restoration initiatives, regenerative agriculture, and integrated crop-livestock-forestry (ICLF) systems. Results demonstrate the framework's sensitivity as an early-warning system: in ICLF and regenerative areas, we observed a significant increase in C-fixation related genes, reflecting enhanced metabolic potential for carbon sequestration. In restoration sites, functional indicators captured early belowground recovery—specifically shifts in microbial nutrient cycling and symbiotic potential—well before changes in vegetation or bulk soil chemistry became detectable. By placing biology on equal footing with chemistry and physics through rigorous, scalable molecular diagnostics, this approach offers an actionable understanding of soil health. The framework supports resilient land

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# Rhizosphere Compartmentation Reveals Conserved and Divergent $CO_2$ Responses Across Wheat Genetic Lineages

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## ABSTRACT

Elevated $CO_2$ alters rhizosphere carbon inputs and microbial activity in wheat, yet it is unclear whether these responses are consistent across genetically distinct wheat lineages and rhizosphere compartments. We compared fungal community composition and nutrient-cycling enzyme activities in the inner and outer rhizosphere of seven ancient wheat varieties and one modern variety grown under ambient and elevated $CO_2$ (+300 ppm) using an open-top chamber field system. Across genotypes, the inner rhizosphere maintained a relatively stable fungal community dominated by Ascomycota under elevated $CO_2$, showing limited compositional change. In contrast, the outer rhizosphere exhibited pronounced shifts in fungal composition, particularly in Basidiomycota and Mucoromycota, together with stronger beta-diversity responses, indicating higher sensitivity to elevated $CO_2$ and greater genotype-dependent variation. Elevated $CO_2$ generally reduced leucine aminopeptidase and β-glucosidase activities across varieties, consistent with increased carbon availability and relative nitrogen limitation. However, several ancient wheat varieties maintained higher β-glucosidase activity or showed enhanced alkaline phosphatase activity, indicating distinct nutrient acquisition strategies under carbon-enriched conditions. These results demonstrate that $CO_2$ responses of the wheat rhizosphere are strongly compartment-dependent and vary among genetic lineages, with ancient wheat varieties showing greater functional flexibility under elevated $CO_2$.

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# The impact of veterinary antibiotics on the functional diversity of microorganisms in agro-sod-podzolic soil

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**ABSTRACT**

To assess the functional diversity of the microbiome, we employed Community Level Physiological Profiling (CLPP) assay—multisubstrate testing (MST) using the Eco-Log system (Russian analog of BiologTM assay) based on standard analitical protocols [1]. The samples were prepared and analyzed according to previously described methods [2].

The study involved a sample from the upper horizon (0–20 cm) of agro-sod-podzolic soil (Albic Glossic Retisols (Loamic, Aric Cutanic, Ochric) in the Chashnikovo Training and Experimental Soil Ecology Center (Solnechnogorsk municipal okrug, Moscow oblast).

Several functional biodiversity indicators were used. These are includes the number of substrates consumed (N) in a range from 0 to 47 that represents here the functional biodiversity index, average metabolic work (W), calculated by summing the non- zero optical densities of cells with substrates consumed dividing by their amount; and the rank distribution shape coefficient of the substrate utilization spectra (d), which applies as a measure of system destabilization or perturbation, with values ranging from 0.01 to 2.00. In the microbial systems studied, the d coefficient serves as a valuable indicator of the health and stability of the soil microbial community, with lower values indicating a thriving and stable community. Conversely, higher values of the coefficient indicate the presence of a disruptive factor affecting the microbial system. Based on the d coefficient, microbial communities can be classified as either good (d = 0.01–0.4), depressed (d = 0.4–0.8), stressed (d = 0.8–1) or damaged (d >1) according to the classification proposed by. Pot experiments were conducted in which *Avena sativa* was grown in sod-podzoic soil contaminated with the antibiotics tylosin, tetracycline, and ciprofloxacin. Uncontaminated soil served as a control. The pots were uniformly illuminated, and the soils were maintained at identical moisture levels. Two months after planting, an analysis was conducted.

Of the antibiotics studied, tylosin proved to be the most characteristic. Soils treated with this antibiotic formed a distinct cluster in a cluster analysis of the spectrum of consumed substrates, suggesting the formation of a specifically functioning community when exposed to this antibiotic. Soils treated with tetracycline and ciprofloxacin did not show a clear specificity. However, tylosin even slightly increased the total metabolic activity of the community, as well as functional biodiversity and stability (changed from 0,6 to 0.1) while other antibiotics had no such effect.

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# Effect of veterinary antibiotics on test plants and enzymes activity and microbiological respiration of sod-podzolic soil

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**ABSTRACT**

Environmental pollution with antibacterial drugs has become one of the most pressing issues. Beyond the widely studied mechanisms of resistance spread and horizontal gene transfer, which necessitate the development of new drugs for effective treatment, there exists a less studied problem of the ecological impact of antibiotics on soil biological health.

Vegetation experiments were conducted, growing *Avena sativa* on sod-podzolic soil contaminated with antibiotics: tylosin (concentration 3.33 mg/kg), tetracycline, and ciprofloxacin (at concentrations of 33.3 mg/kg). Soil without antibiotics served as the control. The vegetation vessels were uniformly illuminated, and identical moisture levels were maintained in all soils. Two months after sowing, enzymatic soil analysis was performed for peroxidase activity [1] and urease activity [2], which are traditional soil bioindicators. Basal and substrate-induced soil respiration were also measured, based on which microbial biomass and metabolic coefficients (q$CO_2$) of the soil under oat cultivation were calculated. Growth parameters of the oats (dry biomass, plant length) were measured. Statistical analysis was performed using the F-test criterion at $\alpha$=0.05.

Microbial biomass in the soil contaminated with tylosin decreased by 4.4%, whereas contamination with tetracycline stimulated it by 6.4%. Ciprofloxacin did not significantly affect microbial biomass. However, the metabolic quotient q$CO_2$ (the ratio of basal to substrate-induced respiration of soil microorganisms) differed only in the ciprofloxacin treatment and was 0.098 compared to 0.131 in the control, indicating a stimulatory effect of ciprofloxacin. Tetracycline inhibited soil enzymatic activity. Peroxidase activity was 13.37% lower, and urease activity was 40.7% lower compared to the control. Tylosin, in contrast, stimulated peroxidase activity (by 31.4%), while urease activity slightly decreased (by 5.3%). Ciprofloxacin stimulated peroxidase activity (by 40.6%) but, like tylosin, inhibited urease activity by 19.7%. The growth parameters of oats showed significant differences under tylosin and tetracycline contamination. Ciprofloxacin did not have a significant effect on plant growth and development.

From the obtained data, we can conclude that antibiotics have a complex effect on soil and plants. In some cases, stimulation of a parameter is observed, while in others, its inhibition occurs.

**Acknowledgments**

This work was funded by the Russian Science Foundation (project no. 25-24-00486).

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# Disentangling plant community and environmental controls on soil-borne pathogens in grassland ecosystems

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## ABSTRACT

Soil-borne pathogens in grassland soils threaten livestock productivity and ecosystem stability. Understanding pathogen distributions and the drivers shaping their population dynamics is thus critical for ecosystem health and management. Here, we surveyed 244 sites across China's natural grasslands and used absolute quantitative amplicon sequencing to quantify soil-borne fungal pathogens in 985 soil samples. We found that temperature strongly shapes the richness, relative abundance, and absolute abundance of soil-borne pathogens. In addition to temperature, relative and absolute pathogen abundance were further moderated by distinct drivers, with relative abundance primarily shaped by plant species richness and absolute abundance by soil properties. We further mapped the current and future distributions of soil-borne pathogens under different climate scenarios, identifying geographically distinct hotspots for different measures of pathogen pressure (*i.e.*, diversity and relative/absolute abundance). Our findings highlight that pathogen richness, relative abundance, and absolute abundance are governed by distinct ecological processes, and we argue that integrated multi-metric assessments are essential for accurate disease risk predictions and to guide adaptive grassland management under climate change.

**Acknowledgments**

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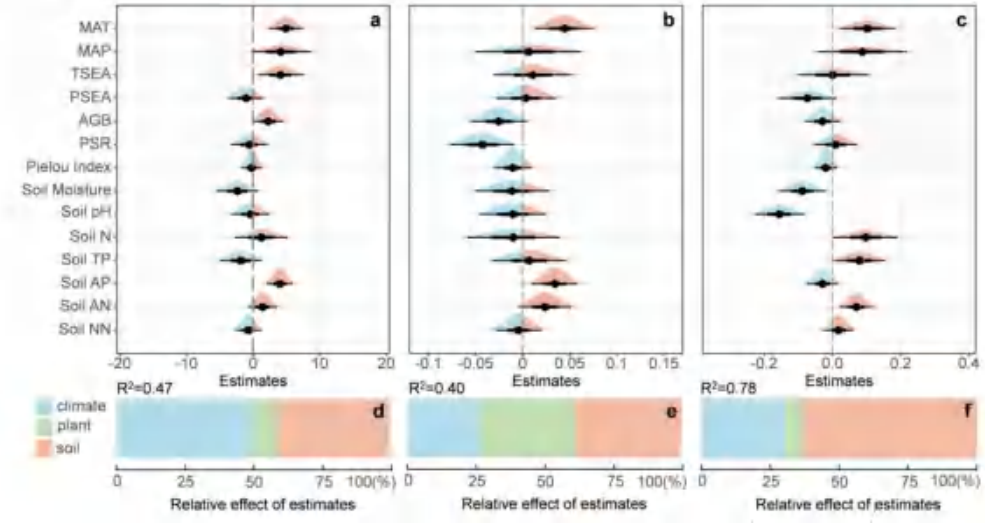



Figure 1. The effects and contributions of climatic factors, plant community characteristics, and soil properties on the richness (*sfpSR*), relative abundance (*sfpRA*), and absolute abundance (*sfpAB*) of soil-borne pathogens. Parameter estimates of Bayesian mixed-effects models for fixed effects on: **a** *sfpSR*, **b** *sfpRA*, and **c** *sfpAB*. The relative contributions of three types of explanatory factors (i.e., climate, plant community, and soil) on **d** *sfpSR*, **e** *sfpRA*, and **f** *sfpAB*.

# Coupling of Intraspecific Root Traits and Rhizosphere Fungal Communities in Cynodon dactylon across Hydrological Gradients of a Reservoir Drawdown Zone

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**ABSTRACT**

Background and Aims Root traits are key predictors in shaping plant-fungal relationships. However, the potential influence of intraspecific root functional traits on plant adaptation, as well as on rhizosphere fungal communities and functional guild dynamics in response to hydrological gradients, remains poorly characterized.

Methods We conducted an in situ field investigation across reservoir riparian zones, quantifying intraspecific root traits, including morphological and architectural traits, and sequencing the rhizosphere fungal community of the dominant species *Cynodon dactylon* (L.) Pers. This study investigated how intraspecific root functional traits correlate with changes in rhizosphere fungal community along hydrological gradients.

Results Our study revealed intraspecific divergence in *C. dactylon* root traits across hydrological gradients, demonstrating a resource collaboration axis spanning from a 'do-it-yourself' ('DIY') strategy characterized by high specific root length to an 'out-sourcing' strategy with thickened roots and elevated root tissue density. The shifts in root traits aligned with opposing microbial responses—general rhizosphere fungi proliferated along the 'DIY' axis at lower elevations, whereas AMF abundance was positively associated with 'out sourcing' traits at higher elevations. Root traits collectively demonstrated stronger explanatory power over AMF community assembly compared to general fungal communities, with root average diameter, fractal abundance and branching rate emerging as key predictors of symbiotic specificity.

Conclusion *C. dactylon* shifts root strategies from 'DIY' to 'out-sourcing' along hydrological gradients, promoting general fungi at low elevations and AMF at high elevations. Root diameter, fractal abundance, and branching rate critically shape AMF assembly, highlighting trait-mediated fungal adaptation. Our findings underscore intraspecific root trait variation as a critical lever through which plants regulate rhizosphere processes, with implications for understanding microbial functions in rhizosphere and the selection of plants for enhanced soil ecosystem services.

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# From Soil to Shoots: Fungal Communities in Pea-Barley Intercropping

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**ABSTRACT**

Cereal–legume intercropping is widely recognized as an environmentally sustainable agricultural practice. It enhances soil biodiversity by increasing the heterogeneity of root exudates, resource availability, and microhabitats, which may influence fungal communities inhabiting soil and plant tissues as components of the holobiont. Understanding how such systems shape fungal communities across plant-associated niches is essential for evaluating their ecological functioning.

Fungal alpha diversity showed a strong niche-dependent pattern, with the highest diversity in bulk soil, followed by the rhizosphere, and markedly lower diversity in roots and especially in aboveground plant tissues. In bulk soil, diversity was highest under barley monocropping, lower under pea monocropping, and intermediate under intercropping. A similar pattern was observed in the rhizosphere. In roots and shoots, fungal diversity was clearly reduced and showed only minor differences among cropping systems. Overall, alpha diversity decreased along the soil–plant continuum, indicating strong host filtering with weak modulation by cropping system.

Beta diversity analyses revealed clear differentiation in fungal community composition among niches, with cropping system effects varying by compartment. Across all niches, fungal communities differed markedly between soil-associated habitats (bulk soil and rhizosphere) and plant-associated habitats (roots and shoots), with additional modulation by cropping system.

In bulk soil and the rhizosphere, fungal communities were dominated by saprotrophic and soil-associated genera, particularly *Mortierella*, *Fusarium*, *Gibellulopsis, Didymella*, and *Cladosporium*. They were only weakly influenced by crop identity. Under intercropping, the rhizosphere showed a more even distribution of dominant genera, indicating increased compositional heterogeneity.

Root-associated fungal communities were more strongly shaped by host selection and were dominated by *Fusarium*, *Gibellulopsis*, *Didymella*, and *Cladosporium*. Differences among cropping systems were more pronounced in roots, with intercropping exhibiting a more balanced dominance structure than monocropping.

Aboveground fungal communities were highly simplified and clearly distinct from those in the belowground compartments, dominated mainly by *Alternaria*, *Cladosporium*, *Didymella,* and *Bipolaris*. Cropping system effects were most potent in shoots, where intercropping promoted a more even community structure, while cereal monocropping showed stronger dominance of individual genera. These results indicate that pea–barley intercropping can subtly reshape fungal community composition, particularly in plant-associated compartments, potentially enhancing microbial heterogeneity in agroecosystems.

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# Regulation of selenium uptake and translocation and hyphal contribution rate in soybean by co-inoculation with AMF and Rhizobium

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**ABSTRACT**

Selenium (Se) is a beneficial trace element that plays an important physiological role in plant growth. Arbuscular mycorrhizal fungi (AMF) and *Rhizobium* are common symbiotic microorganisms in the soybean rhizosphere. However, under inoculation conditions, the contribution of the AMF hyphal pathway to Se uptake and its uptake and translocation mechanisms remain poorly understood. In this study, a rhizobox experiment was conducted with three inoculation treatments: non-inoculation (NM), single inoculation with *Funneliformis mosseae* (*F.m*), and co-inoculation with *Funneliformis mosseae* and *Rhizobium* (*F.m+Rh*), combined with four selenite application levels: (1) no selenite addition to either the rhizosphere or hyphal compartments (0-0-0); (2) selenite addition only to the rhizosphere compartment (0-Se-0); (3) selenite addition only to the hyphal compartment (Se-0-Se); and (4) selenite addition to both compartments (Se-Se-Se). The results showed that exogenous selenite application and co-inoculation significantly increased the photosynthetic rate of soybean, promoted root growth, and enhanced nutrient uptake, thereby markedly improving plant growth ($p < 0.05$). At the same selenite level, Se concentrations in both the shoots and roots of soybean under the co-inoculation treatment were significantly higher than those under single AMF inoculation (5.74%-6.69%) and NM treatment (13.44%-15.77%; $p < 0.05$). Selenite application to the hyphal compartment significantly increased Se uptake by soybean, indicating that AMF hyphae were able to cross the rhizobox barrier and effectively acquire Se from the hyphal compartment. Notably, under single AMF inoculation, the contribution of the hyphal pathway to Se uptake ranged from 7.12% to 8.28%; whereas under co-inoculation with *Rhizobium* and AMF, the synergistic effect of *Rhizobium* significantly enhanced the Se uptake capacity of the AMF hyphal pathway, increasing its contribution to 12.84%–14.31%. Overall, the synergistic interaction between AMF and *Rhizobium* markedly enhanced the contribution of the hyphal pathway to Se uptake in soybean. This study offers new insights into the systematic understanding of Se uptake and transport mediated by the mycorrhizal hyphal pathway, and provides theoretical support for improving Se utilization efficiency and advancing sustainable production of Se-enriched soybeans.

# Driving Mechanisms of Antibiotic Resistance Genes in Urban Forest Soils

**ABSTRACT**

Urban forest soils play a critical role in maintaining urban ecosystem services but are increasingly subjected to anthropogenic pressures, including contamination by heavy metals and polycyclic aromatic hydrocarbons (PAHs). Understanding how urbanization shapes soil biogeochemical processes, microbial community structure, and the propagation of antibiotic resistance genes (ARGs) is essential for assessing ecosystem health and risks. This study investigated the spatial patterns of soil chemical properties, heavy metals, PAHs, nutrient cycling functional genes (C, N, P), ARGs, and bacterial communities across urban-suburban gradients in urban forest soils. Results showed acidic soil conditions (pH < 7) across all sites, with urban centers exhibiting higher levels of nutrients (K, Ca), while cation exchange capacity (CEC) and total organic carbon (TOC) were significantly elevated in suburban areas. A clear urbanization gradient was observed in heavy metal accumulation: Zn and Pb were most enriched at site S, Cr peaked at site G, and V and Ni concentrations were higher in urban (R, G) than in suburban (S, M) sites. No significant spatial variation was detected for arsenic (As), and PAH concentrations did not differ significantly between urban and suburban zones, although residential areas showed the highest concentrations for most PAHs.

A total of 198 ARG subtypes associated with 20 antibiotic classes were detected. Multidrug resistance genes were the most abundant, followed by genes conferring resistance to macrolides-lincosamides-streptogramines, vancomycin , bacitracin, and beta-lactams . Efflux pumps were the predominant resistance mechanism. Significant differences in ARG composition were observed along the urbanization gradient (PERMANOVA: $R^2 = 0.359$, $p = 0.001$), with the highest Shannon diversity at site M and the lowest at site U. Bacterial alpha diversity was higher in suburban areas, and community structure differed across the gradient, governed mainly by stochastic assembly. Potential ARG hosts were primarily Acidobacteria and Proteobacteria, with Acidobacteria more abundant in suburban zones. ARGs were positively correlated with As but negatively correlated with PAHs (Phe, Chr, BbF). Furthermore, PLS-PM analysis indicated that ARGs were collectively influenced by heavy metals, PAHs, keystone taxa, and nutrient cycling genes, with heavy metals and keystone taxa promoting ARG abundance, while PAHs exhibited an inhibitory effect.

In conclusion, urbanization significantly alters soil biogeochemical properties, microbial functional potential, and ARG dissemination in urban forest ecosystems. The interplay between heavy metals, PAHs, keystone bacterial taxa, and nutrient cycling genes collectively modulates ARG dynamics. These findings underscore the need for integrated management strategies to mitigate contamination and preserve soil ecological functions in urban forests.

# Urbanization-driven forest soil greenhouse gas emissions: Insights from the role of soil bacteria in carbon and nitrogen cycling using a metagenomic approach

**ABSTRACT**

The escalation of greenhouse gas (GHG) emissions from soils, driven by rising population densities and urban sprawl, underscores the critical role of soil microbial communities in urban forests in both the production and consumption of GHGs, thereby supporting sustainable green development. However, the functional roles and underlying mechanisms of soil bacteria in regulating GHG emissions from forests during urbanization remain insufficiently understood. In this study, we quantified the fluxes of carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) from Cinnamomum camphora forest soils along an urbanization gradient. Using 16S rRNA amplicon sequencing and metagenomic approaches, we systematically analyzed the structure and potential functions of soil bacterial communities involved in carbon (C) and nitrogen (N) cycling.

Our results demonstrated that $CH_4$ and $CO_2$ emissions were significantly higher in urban forest soils (sites U and G) compared to suburban soils (sites S and M). Notably, $N_2O$ emissions at the urban center (site U) exceeded those at the other three sites by 24.0% (G), 13.8% (S), and 13.5% (M). This emission pattern was closely associated with increased bacterial alpha diversity, enhanced microbial interactions, and elevated abundances of C- and N-cycling genes, particularly those involved in denitrification. Furthermore, soil pH and metal content (K, Ca, Mg) influenced the distribution of key bacterial taxa (e.g., Methylomirabilota, Acidobacteriota, and Proteobacteria) and functional genes (e.g., napA, nosZ, nrfA, nifH) implicated in $N_2O$ reduction. Heavy metal content (Fe, Cr, Pb) emerged as a primary driver of $CH_4$ emissions, likely through modulation of methanogenic (e.g., Desulfobacterota) and methanotrophic (e.g., Proteobacteria, Actinobacteriota, Patescibacteria) bacterial communities.

This study further reveals that the structure and function of soil microbial communities play a crucial regulatory role in GHG emissions. Urbanization-induced changes in environmental factors, such as nutrient inputs, heavy metal accumulation, and alterations in soil physicochemical properties directly affect microbial metabolic pathways and indirectly influence C and N transformation processes by reshaping inter-species interaction networks. Consequently, scientifically informed urban planning and near-nature forest management strategies that optimize soil microbial community structure and enhance carbon sequestration and nitrogen conversion efficiencies may serve as effective approaches to mitigate urban GHG emissions and promote sustainable urban development. These findings provide a theoretical foundation and practical guidance for microbial-mediated low-carbon management of urban forest ecosystems.

# Can soil protists improve plant growth?

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**ABSTRACT**

Plant-associated microbiome is considered to play a crucial role in enhancing plant nutrient cycle, plant growth promotion, plant disease suppression and stress tolerance. However, we still lack knowledge about roles of soil protists in plant growth. Here, we elucidate effects of soil protists on plant growth and their association with bacterial communities by growing tomato plants in an agricultural soil inoculated with soil protists via a pot experiment. Our results reveal that protists significantly promoted the plant growth of tomato. Soil protists increased plant length and dry weight, as well as alpha diversity (Shannon index) of bacteria. These protists are strongly associated with plant-beneficial bacterial taxa in performing their functions. Novel findings in this study advance our understanding about the importance of protists in soil and plant microbiomes, implicating potential applications of beneficial protists and bacteria as biofertilizers or bio-stimulants to improve crop performance and sustain agricultural production in future.

**Acknowledgments**

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# From Global Carbon Store to Climate Feedback: 25 Years of the Enzymic Latch in Wetlands

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**ABSTRACT**

Peatlands and other wetlands store a disproportionate share of the Earth's soil carbon because primary production has long outpaced microbial decomposition under waterlogged conditions. The enzymic latch hypothesis, proposed in 2001, offered a mechanistic explanation: environmental constraints such as $O_2$ availability, suppress phenol oxidase, allowing phenolic compounds to accumulate and inhibit key hydrolase enzymes, thereby "locking" organic matter into place. Over the subsequent twenty-five years, this concept has significantly shaped thinking, experimentation, and management strategies in wetland biogeochemistry.

This talk will first revisit the original evidence for the latch and its extension from northern peat bogs to fens, marshes, and mangrove soils, where phenolic inhibition and redox constraints have been invoked to explain high carbon storage and distinctive greenhouse gas fluxes. It will then synthesise a growing body of work that refines or challenges the hypothesis, including studies that find only mixed or ecosystem-specific links between phenolics, enzyme activities, and decomposition, or that highlight the controlling roles of pH, plant functional groups, and microbial community composition. Finally, it will consider how the enzymic latch framework has informed peatland restoration and "engineering" approaches, such as rewetting, phenolic amendments, and mineral interventions, and assess what this means for predicting wetland feedbacks to climate change in a future of altered hydrology, salinity, and disturbance regimes.

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# Nonlinear response of anaerobic methane oxidation to water table drawdown in peatlands under climate warming

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**ABSTRACT**

Anaerobic oxidation of methane (AOM) is a significant but underappreciated methane sink in global wetlands, yet its mechanistic response to hydrological gradients due to climate warming and drought remains poorly unexplored. Using $^{13}CH_4$-labelled microcosm incubations in peat soils across water-table depth (WTD, from 15-45 cm) and temperature gradients (5, 15, 25°C), we observed that AOM rates increased with increased WTD irrespective of incubation temperature, that reached a peak AOM rate (1.68 ± 0.25 μg C $g^{-1}$ peat $d^{-1}$) at ~30 cm WTD, thus decline sharply beyond this depth. Random forest and mixed linear models illustrated this phenomenon was driven by the substrate availability, alternative electron acceptor content (Fe(III)), and microbial metabolic activities (RT-qPCR data). Thermodynamic assessment indicates that the 30 cm WTD also represented the threshold for AOM temperature responsiveness; deeper drainage shifts it into a diffusion-limited regime, with higher $Q_{10}$ values reflecting an "energy-compensation paradox". Moreover, combing with a global meta-analysis across water-table gradients in peatlands, that corroborated the nonlinear response of AOM to water table decline. We are the first to uncover an eco-thermodynamic threshold mechanism whereby WTD regulates AOM, thereby providing critical insights for improving methane-cycle models and informing peatland management and restoration.

**Acknowledgments**

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# Exploiting Soil Recalcitrant Phosphorus (P) Drives Invasion: Adaptive P-acquisition Strategies of Spartina alterniflora in Chinese Coast

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## ABSTRACT

**Background:** The extensive invasion of *Spartina alterniflora* across the Chinese coast poses a major ecological threat [1,2]. Although its successful expansion often faces the widespread phosphorus (P) limitation common in coastal wetlands [3], the intrinsic physiological and ecological mechanisms supporting its persistent survival and expansion in low-P environments—particularly whether its soil P acquisition strategy has undergone adaptive shifts—remain unknown.

**Methods:** To systematically reveal the biogeochemical mechanisms underlying its invasion success, we conducted a large-scale comparative study spanning nearly a 20° of latitude across its native (North America, 15 sites) and invaded ranges (China, 10 sites). This study is the first to analyze the adaptive mechanisms of *S. alterniflora* from an integrated perspective of "soil P forms—plant P-acquisition strategies—resource allocation trade-offs." We adopted a sequential biologically-based-phosphorus (BBP) fractionation method to quantify the composition of the soil bioavailable P pools by simulating rhizosphere processes (such as carboxylates exudation, enzymatic hydrolysis, and proton secretion), and combined this with the analysis of plant traits and environmental factors to explore the intrinsic link between P-acquisition strategies and growth-reproduction.

**Results:** The soil total phosphorus (TP), inorganic phosphorus, and active P fractions (especially citrate-P) in the Chinese invaded wetlands were significantly lower than those in their native North American salt marshes, confirming the typical P-limitation characteristic of China's coastal wetlands. However, contrary to the low-nutrient background, the proportion of total BBP-extracted P in the invaded soil was significantly higher than that in the native range (+24.5%), and this proportion showed a significantly increasing trend with increasing latitude. This difference primarily stems from the substantial portion of sparingly soluble mineral-bound HCl-P (accounting for 83.6% of TP) in the invaded soil, whereas the native range was dominated by the more labile citrate-P (accounting for 40.6%). This shift demonstrates that *S. alterniflora* can convert sparingly soluble P into available P through mechanisms such as rhizosphere acidification and enzymatic mineralization, thereby forming a "low stock-high efficiency" resource acquisition strategy. Plant trait—soil P fraction association analysis further indicated that the invaded populations exhibit a significantly different P utilization—trait response pattern compared to the native populations. Within the invaded range, $CaCl_2$-P and HCl-P significantly promoted seed set rate, with weaker promoting effects on above-ground biomass and plant height; conversely, in the native range, growth was primarily promoted by more labile P such as citrate-P, with a weak correlation to reproduction. This suggests that in the invaded wetlands, *S. alterniflora* prioritizes the allocation of mobilized P to reproductive organs rather than sustaining high biomass production. As latitude increases, the proportion of HCl-P significantly rises, and the strong correlation between seed set and HCl-P indicates that, in high-latitude soils dominated by mineral-bound P, *S. alterniflora* enhances its ability to mobilize recalcitrant P and preferentially allocates the acquired P to reproduction. This mechanism provides a clear explanation for the “higher reproductive output at higher latitudes” observed along the Chinese coast. This "P-mining" strategy—enables it to secure offspring dispersal and population expansion in P-limited environments, thus constituting the core physiological and ecological mechanism of its invasion success.

**Conclusion:** In summary, this study revealed the key mechanisms underlying the successful invasion of *S. alterniflora* in China's coastal wetlands: (1) The invaded area is characterized by soil background features of strong P fixation and low P bioavailability, with its P pool dominated by the sparingly soluble mineral-bound HCl-P. *S. alterniflora* can efficiently mobilize these recalcitrant P fraction through mechanisms such as rhizosphere acidification, complexation, and enzymatic mineralization, significantly increasing the proportion of potentially bioavailable P in TP. (2) The mobilized P is preferentially invested in reproductive structures rather than being used to substantially increase vegetative growth, thus forming a resource allocation strategy of "low-cost growth—high-efficiency reproduction," which significantly enhances its dispersal and invasion ability. (3) This strategy is significantly strengthened along the latitudinal gradient, exhibiting higher recalcitrant P mobilization capacity and stronger reproductive inclination in high-latitude, P-fixation-intensive environments, reflecting adaptive resource reallocation driven by nutrient stress. This mechanism implies that the mobilization of soil stable P pools by *S. alterniflora* may accelerate the P turnover in wetland ecosystems through potentially impacting the ecosystem C-N-P dynamics, and further the long-term carbon sequestration potential and ecosystem stability of wetlands. Therefore, understanding this P-driven invasion mechanism provides a new theoretical basis for predicting plant invasion trajectories, formulating nutrient management-based wetland restoration strategies.

**Key words**
*Spartina alterniflora*; biological invasion; phosphorus-acquisition strategies; biologically-based phosphorus fractionation; coastal wetlands

**Graphic ABSTRACT**



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# Millimeter-scale niche differentiation of N-cycling microorganisms across the soil-water interface has implications for $N_2O$ emissions from wetlands

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**ABSTRACT**

Wetlands can be a significant source of $N_2O$ under current global climate change regime with the soil-water interface representing a biogeochemical hotspot for microbial activity. However, the role of soil-water interface in controlling $N_2O$ emissions remains poorly understood. We hypothesized that the millimeter-scale redox gradient across the soil-water interface generates corresponding distinct niche for N-cycling microorganisms that collectively regulate the production and consumption of $N_2O$ over the same spatial scale. The abundance, transcriptional activity and spatial organization of different N-cycling guilds across the soil-water interface were characterized in mesocosms from three different paddy soils with different $N_2O$ emissions. Results demonstrated millimeter-scale stratification of N-cycling microbial activity across the soil-water interface, and in particular within the first 10 mm of flooded soils. Ammonia-oxidizing microorganisms were only transcriptionally active in the top 4 mm, suggesting a previously underestimated contribution to $N_2O$ emissions from wetlands. Variation in $N_2O$ accumulation was observed across the soil-water interface, with the highest concentrations measured at either the soil-water interface or in the deeper anoxic layer of paddy soils. Despite this difference, $N_2O$-reducing microorganisms exhibited high transcriptional activity at the soil-water interface in all soils, suggesting that there is a microbial-mediated sink for $N_2O$ across the soil-water interface that can reduce $N_2O$ produced from both oxic and anoxic layers. This work demonstrates an underappreciated and essential role of the microbial hot zones at soil-water interface in regulating $N_2O$ emissions from wetlands.

# Climate warming suppresses the preservation of metal-associated organic carbon in peatlands

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## ABSTRACT

Peatlands represent a critical terrestrial carbon sink, yet the stability of distinct organic carbon pools under climate warming remains poorly understood. Here, we investigated the distribution and drivers of metal-associated organic carbon (Bound OC) in peat cores along an elevational gradient (620-2626 m) in the Changbai Mountains to elucidate its response to climate warming. Our results showed a marked heterogeneity in Bound OC and its properties with peat depth. The contents and proportion of Bound OC, as well as reactive iron contents, were significantly higher in anoxic environments than in oxic environments, with *Sphagnum*-dominated peatlands under anoxic conditions exhibiting the highest values. Although the Bound OC proportion was generally less than 10%, the OC:(0.5Fe+Al) molar ratio was approximately 20, suggesting that Bound OC primarily forms through co-precipitation and confirming the operation of an 'iron gate' mechanism in carbon-rich peatlands. Mixed linear models revealed that increased peat temperature, serving as a proxy for climate warming, led to a significant decrease in Bound OC contents and proportion, as well as in the contents of reactive metal oxides and their activation degrees. Furthermore, the influence of vegetation (*Sphagnum* vs. non-*Sphagnum*) on Bound OC and its properties, quantified using site-weighted response ratios, was strongly mediated by redox conditions. In oxic environments, *Sphagnum* sites enhanced the Bound OC proportion and OC:(0.5Fe+Al) molar ratio compared to non-*Sphagnum* sites; however, this positive effect diminished with rising temperature. Conversely, in anoxic environments, *Sphagnum* was initially less effective at promoting these properties, yet this disadvantage attenuated as temperature increased. Microbial analyses and structural equation modeling demonstrated that *Sphagnum* modulates Bound OC dynamics by regulating iron respiration and microbial biomass carbon, with its role as a "rusty carbon sink" engineer being dependent on redox status. Specifically, warming suppressed Bound OC proportion in oxic environments by reducing *Sphagnum* coverage and metal oxides, whereas in anoxic environments, it acted by stimulating microbial activity and diminishing metal oxides. In summary, this work demonstrates that climate warming threatens the peatland carbon stock by disrupting mineral protection mechanisms and highlights the necessity of incorporating the interactive effects of redox potential and vegetation into climate-carbon models.

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# Nitrogen input regulates soil carbon fixation via microbial-driven mineral-associated organic carbon formation in wetlands

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**ABSTRACT**

Nitrogen (N) availability critically regulates soil carbon (C) fixation in wetland ecosystems, yet the microbial mechanisms driving this process remain unresolved. Through a gradient of N inputs (CK:0, N1: 3g N $m^{-2}$ $yr^{-1}$, N2: 10 g N $m^{-2}$ $yr^{-1}$, N3: 17 g N $m^{-2}$ $yr^{-1}$, N4: 24 g N $m^{-2}$ $yr^{-1}$) combined with metagenomic sequencing, we demonstrate that moderate N (N2) input significantly enhanced soil key hydrolytic enzyme activities (e.g., β-glucosidase, cellobiohydrolase, N-acetylglucosaminidase), increased microbial biomass C and N contents, and promoted the accumulation of total C, N and phosphorus in the surface soil (0-15 cm). In contrast, high N (N4) input suppressed these enzyme activities and led to significant soil acidification and a decline in nutrient availability. Soil C fixation capacity, indicated by RubisCO activity and K01681 gene abundance, peaked under N2 treatment but declined under N4 treatment. Metagenomic profiling showed that N2 treatment enriched several microbial C fixation pathways (e.g., reductive citrate cycle, dicarboxylate-hydroxybutyrate cycle, 3-hydroxypropionate bi-cycle, and calvin-benson-bassham cycle), whereas all were suppressed by N4 treatment. High N also reduced microbial diversity, enriched acid-tolerant Proteobacteria, and suppressed Actinobacteriota. Correlation and structural equation modeling demonstrated that N input shaped mineral-associated organic C (MAOC) dynamics primarily through its restructuring of the microbial community, which in turn governed C fixation capacity. Our findings establish a mechanistic framework linking N-induced changes in soil properties and microbial traits to C fixation, providing insights for predicting wetland C dynamics under nutrient enrichment.

**Keywords:** Nitrogen enrichment, Microbial communities, Wetland carbon fixation, Nutrient cycling

# Thiol-activated ROS generation by particulate organic matter: The overlooked role of interface-accelerated organic radical chain reaction

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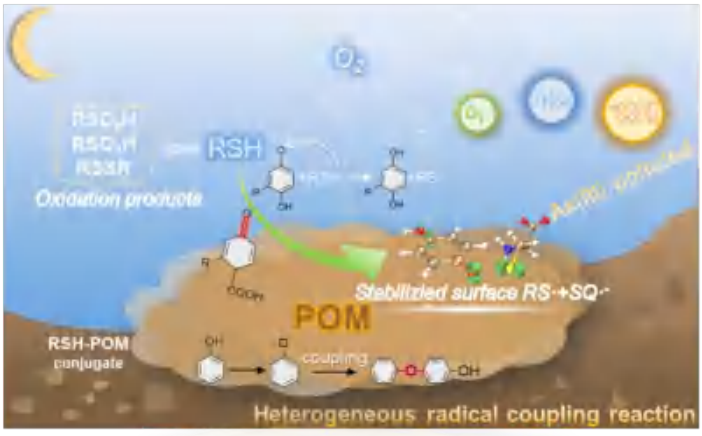
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**ABSTRACT**

Particulate organic matter (POM), a major component of natural organic matter (NOM) in aquatic systems, plays a crucial but poorly understood role in dark reactive oxygen species (ROS) generation. The mechanisms of POM-mediated ROS formation under dark conditions, especially through interactions with environmental reductants, remain unclear. This study revealed that thiols exhibited superior activation capacity for POM-mediated ROS production, with hydroxyl radical (•OH) yields 1.4-6.1 times higher than that of dissolved Fe(II). Batch experiments demonstrated that thiol donated electrons via -SH groups, with surface-active quinones on POM facilitating electron transfer, as evidenced by 13C NMR, FTIR, and XPS analyses. Model experiment and DFT calculation confirmed that quinones lower the energy barrier for Cys oxidation, thereby initiating RS• and SQ•- production through organic free radical chain reactions. This process facilitated •OH production in Cys/BQ system (120.7 μM), which was further confirmed by the marginal •OH enhancement in Fe(II)/BQ system (from 9.9 ± 0.5 μM to 16.9 ± 0.2 μM). Kaolinite particulates in POM further enhanced •OH yields by 88% through surface-mediated radical chain propagation. This ROS-mediated process not only enhanced Cys transformation, but also altered POM surface properties and facilitated As(III) oxidation. These findings provide a deeper understanding of the role of POM in environmental redox chemistry and its implications for contaminant transformation and geochemical cycling, and pave the way for further research into the behavior of free radical intermediates in environmental applications.

**Keywords:** particulate organic matter, thiol, reactive oxygen species, radical coupling, organo-mineral interaction

Graphical ABSTRACTs:




**Acknowledgments**

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# Water level regulation for reducing carbon emissions in urban restored wetlands

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**ABSTRACT**

Iron reduction and oxidation play a key role in stabilizing soil organic carbon (SOC). However, few studies have examined the impact of water level regulation on iron cycle and carbon emissions in restored wetlands. Here, we conducted in-situ measurements of $CO_2$ and $CH_4$ fluxes and sediment physicochemical properties at sites with different water depths in Haizhu Ramsar wetland of the Pearl River Delta, China. We found that water level fluctuations contributed to higher carbon emissions from shallow marshes than from open water zones. Then, we collected 36 soil cores from the shallow marshes of the wetland and did a water level and Fe(II) concentration manipulation experiment. We detected carbon emissions of 2.78, 3.13, and 2.88 mg·C $m^{-2}$·$d^{-1}$ when the soil cores were submerged in 15, 30, and 45 cm of water, respectively. When water level increased, soil oxygen declined, Fe(II) increased, Fe(III) decreased, and SOC bound to iron minerals accumulated. Microbial community analysis revealed that the relative abundances of iron-reducing bacteria did not significantly change but methanogens increased with water level. Adding 0.01 M Fe(II) strengthened carbon emissions, and the enhancement was smaller when water level was higher. Overall, our findings suggest that deltaic tidal wetland restoration could reduce soil carbon emissions when water level was raised.

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# Planting density constrains soil organic carbon pools during native plant restoration following Spartina alterniflora removal across invasion chronosequences

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**ABSTRACT**

Coastal wetlands are important global carbon sinks but are increasingly affected by biological invasions and intensive management. Large-scale removal of *Spartina alterniflora* alters soil environments in Chinese coastal wetlands, yet its effects on soil organic carbon (SOC) sequestration and microbial mechanisms remain unclear.

Here, we conducted a controlled pot experiment using soils from the Yellow River Delta representing native *Suaeda salsa* marshes and areas previously invaded by *S. alterniflora* for 7 and 16 years. Native vegetation was restored under low and high plant density treatments. We combined metagenomic sequencing with microbial network and metagenome-assembled genome (MAG) analyses to examine how invasion history and plant density interactively regulate SOC dynamics. SOC content and SOC/TN increased significantly with increasing invasion duration. High plant density restoration enhanced SOC accumulation in invaded soils but had no significant effect in native soils. SOC accumulation did not increase monotonically with invasion duration; instead, significant gains occurred only under high plant density.

The abundance of carbohydrate-active enzyme (CAZyme) genes showed inconsistent responses to invasion history and plant density and was only weakly correlated with SOC accumulation. In contrast, microbial network analysis revealed that invasion duration increased network complexity, and high plant density further enhanced this effect. Functional redundancy (FR), quantified as the average number of microbial taxa associated with each CAZyme gene, increased markedly with invasion duration under high plant density and showed a strong positive correlation with SOC accumulation. MAG analysis indicated that enhanced functional redundancy was driven by community turnover and increasingly deterministic assembly processes. Community assembly analysis further showed that deterministic processes dominated under long invasion duration, particularly under high plant density. Random forest and linear regression analyses identified SOC, SOC/TN, and pH as key drivers of FR.

Together, our results demonstrate that restoration outcomes following *S. alterniflora* management depend on invasion history, with plant density regulating SOC sequestration primarily through microbial functional redundancy rather than gene abundance.

# Impact of Phenolic Additions on Microbial Properties of Peatland

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**ABSTRACT**

Peatlands represent a critical global carbon reservoir, storing up to 1,000 Gt of carbon in the form of undecomposed organic matter. This immense storage capacity arises from a persistent imbalance in which the rate of organic matter decomposition is substantially lower than that of primary production. Understanding the mechanisms that suppress decomposition in these ecosystems is therefore of paramount importance.

A key mechanism underlying this imbalance is the waterlogged, anaerobic condition characteristic of peatlands, which severely limits oxygen availability. Freeman et al. (2001) proposed the Enzyme Latch Hypothesis (ELH) to explain how anaerobiosis stabilizes peat carbon. According to the ELH, oxygen limitation suppresses the activity of phenol oxidase, an enzyme responsible for degrading phenolic compounds. Phenolics, which are abundant in peatlands, are potent inhibitors of hydrolytic enzymes essential for organic matter decomposition. Consequently, under anaerobic conditions, phenolics accumulate and form an “enzyme latch” that constrains microbial activity and stabilizes large carbon stocks.

In this study, we investigated eight environmental conditions (e.g., water table depth, vegetation type, and peat excavation history) across three major experimental site types to examine general responses across peatlands in different states in Canada. Two phenolic materials—*Picea mariana* wood chips and aged roots derived from peat harrowing—were applied at a rate of 2 kg $m^{-2}$. Soil samples were collected and analyzed one year after application. Contrary to our hypothesis, phenolic additions increased the abundances of bacteria and Archaea, suggesting that these phenolic materials acted as carbon sources rather than inhibitory compounds for prokaryotic communities. In contrast, fungal abundances declined following phenolic additions on several occasions. We speculate that phenolic materials may selectively inhibit fungal proliferation in peatlands, thereby slowing the decomposition of recalcitrant carbon pools.

# Soil structure determines dissolved organic carbon release from peat soils

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**ABSTRACT**

Preferential flow is widespread in peat soils but has been little studied, particularly in relation to dissolved organic carbon (DOC) transport. To investigate its occurrence, extent, and dominant pathways, undisturbed peat cores were collected from drained, rewetted, and natural peatlands in Mecklenburg-Western Pomerania, Germany, with two replicates per site. A multisegment percolation system (MSPS) with ten individual collection zones was used, and artificial rainfall (10 mm $day^{-1}$) was applied to each soil column for 40 days. The volume and DOC concentration of percolated water were measured to clearly distinguish preferential flow from matrix flow. Additionally, X-ray computed tomography (CT) was performed to characterize soil structure, macroporosity, and pore connectivity. Preferential flow accounted for over 90% of total DOC export, indicating it as the dominant transport pathway in peat soils. CT analyses revealed that air-filled porosity (AP) and maximum macropore length (ML) are the main parameters controlling macropore flow. These results demonstrate that preferential flow is prevalent in peat soils and plays a key role in DOC mobilization, highlighting the importance of pore connectivity in governing water and carbon dynamics in peatland ecosystems.

**Keywords:** Peat soils; Preferential flow; Dissolved organic carbon (DOC); Macroporosity; X-ray computed tomography (CT)

# Microbially Mediated Mechanisms of PFAS-Induced Soil Carbon Priming Effects in Mangrove Ecosystems

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**ABSTRACT**

Coastal wetlands, particularly mangrove ecosystems, store disproportionately large soil carbon (C) pools yet are increasingly exposed to per- and polyfluoroalkyl substances (PFAS) derived from urbanization and industrial activities. While PFAS toxicity has received growing attention, their capacity to alter soil organic matter (SOM) decomposition and carbon priming effects mediated by microbial processes remains poorly constrained, especially in coastal soils differing in carbon and nutrient status.

Here, we investigate how a legacy PFAS (perfluorooctane sulfonate, PFOS) and a short-chain replacement (perfluorobutane sulfonate, PFBS) regulate microbially driven C processing in a mangrove soil and an adjacent shrub soil from a rapidly urbanizing coastal region in South China. Soils were exposed to PFOS or PFBS across concentration gradients of 0, 10, and 100 mg $Kg^{-1}$ soil, with and without the direct addition of $^{13}C$-labeled glucose as a readily available carbon substrate. This design allows us to quantify PFAS-induced changes in total soil respiration and to partition $CO_2$ sources between native SOM and added substrate based on the isotopic composition of respired $CO_2$.

Our results reveal that PFAS exposure can significantly modify soil C mineralization rates and alter the coupling between microbial substrate utilization and SOM turnover, with contrasting responses between mangrove and shrub soils under substrate-amended conditions. To resolve the microbial mechanisms underlying these process-level responses, we integrate community composition analyses (16S rRNA and ITS amplicon sequencing), metagenomic functional profiling, and DNA-stable isotope probing to identify actively assimilating microbial populations and PFAS-sensitive carbon-use pathways.

By explicitly linking PFAS exposure to microbial carbon-use strategies and priming dynamics, this study provides mechanistic insights into the vulnerability of coastal wetland carbon stocks under emerging contaminant pressures, with implications for blue carbon conservation and climate-resilient management of contaminated coastal ecosystems.

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# The Water Table Crux for Peatland Recovery

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**ABSTRACT**

Anthropogenic activities such as drainage and rewetting substantially modify carbon and nutrient dynamics as well as biodiversity in peatlands. Rewetting has been suggested as a potential strategy to restore peatland functions and mitigate carbon loss, though the results are not consistently as effective as envisioned. Here, we synthesize data from more than 200 peatlands across mid- and high-latitude regions—including natural, drained, and rewetted sites—to examine the influence of water table level on net carbon dioxide ($CO_2$) flux (i.e., net ecosystem production (NEP)) and methane ($CH_4$) emissions, plant biodiversity, and pore water quality. Our findings reveal that as the water table rises from –80 to 120 cm, $CO_2$ emissions decrease progressively, and CH4 emissions increase significantly. In shallow peatland lakes formed after rewetting, where the water table is at least 20 cm above the ground, the reductions in $CO_2$ emissions may be countered by elevated $CH_4$ emissions. This balance could lead to neutral net carbon radiative forcing (NEP and $CH_4$) over 300-year period with considerable uncertainty. The flooded 'rewetted' peatlands exhibit low species richness of peatland vegetation and higher concentrations of dissolved organic carbon, ammonium, and phosphate in pore water. This study further emphasizes that active rewetting strategies, such as maintaining water tables near the ground surface (–20 to 10 cm) and reintroducing peatland plants, can not only enhance carbon and nutrient sequestration but also promote plant biodiversity, as evidenced by the return of the abundance of peatland-specialist species.

**Keywords:** Peatlands; Water table; Rewetting; Carbon flux; Biodiversity

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# Role of Iron Minerals in Carbon Stabilization in Redox-Active Ecosystems

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**ABSTRACT**

Coastal ecosystems are widely recognized for the services they provide, especially coastal protection and carbon sequestration (Kauffman et al., 2020). The global average carbon sequestration rate reaches 174 g C $m^{-2}$ $y^{-1}$, and carbon storage can reach 937 t C $ha^{-1}$ (Alongi, 2014), and the value of these services has been estimated at US $194,000 $ha^{-1}$ $yr^{-1}$ (Costanza et al., 2014; Arnaud et al., 2023). However, despite the clear benefits that coastal ecosystems provide, the impacts of soil attributes, especially redox chemistry involving Fe, on carbon fluxes remain uncertain and unquantified. Soil carbon storage is strongly influenced by environmental variables such as nutrient availability, oscillations in tide, light, temperature, and salinity, which can be highly heterogeneous across space and time (Capooci, 2022; Seyfferth et al., 2020). This is especially important in such diverse lithoclimatic conditions as the ones observed along the Brazilian coastline (Ferreira et al., 2021, 2022, 2024), which encompasses approximately 10% of the world's total mangrove areas. In this sense, this work aimed to test machine learning approaches to predict total organic carbon concentration in contrasting coastal soils along the Brazilian coast. The dataset for this work represented three contrasting coastal ecosystems, mangroves, seagrass meadows, and hypersaline tidal flats, encompassing a wide spectrum of environmental conditions, vegetation types, and hydrological characteristics within coastal wetlands. A total of 455 soil samples were collected from the three studied ecosystems: 328 from mangroves, 75 from seagrass meadows, and 52 from HTF. The dataset comprised physicochemical data collected in field (pH, redox potential - Eh, and electric conductivity - EC) as well as soil parameters determined in the laboratory (total organic carbon - TOC, iron geochemical fractionation: exchangeable (EX), associated with carbonates (CA), associated with ferrhydrite (FR), associated with lepidocrocite (LP), associated with well-crystaline oxides (OX), associated with pyrite (PY) and total Fe concentration in the soils). Information about the collection points, such as latitude and seasons, was also added to the dataset. We used the Random Forest (RF) algorithm to model and predict Total Organic Carbon (TOC) based on a set of environmental and soil variables. All analyses were performed in R (version 4.4.2). Initial exploratory data analysis was conducted using the explore package, and variables deemed redundant or irrelevant were excluded. The dataset was cleaned by removing rows with missing values using na.omit(), and variable names were standardized with the janitor::clean_names() function. The RF model was implemented with the explore::explain_forest() function, with TOC as the response variable and the remaining variables as predictors. Model performance was evaluated using the Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination ($R^2$). These metrics were calculated by comparing the predicted TOC values against the observed values within the dataset, providing an assessment of prediction accuracy and model fit. The model explained approximately 58% of the variance in TOC (pseudo-$R^2$ = 0.5791), with a mean squared residual of 0.98. Among the most influential variables were ecosystem type, poorly crystalline iron (Fe_LP), latitude, and total iron content, indicating that ecological, physicochemical, geochemical, and spatial factors play key roles in shaping TOC in vegetated coastal soils in Brazil. The results showed a strong control of ecosystem type, latitude, and iron forms on total organic carbon (TOC) in soils accross Brazil coastline. By enabling TOC assessments in blue carbon (BC) ecosystems, this work can provide future guidance on modeling organic carbon in tropical BC ecosystems as well as contribute to Brazil's progress toward its nationally determined contribution (NDC) targets related to ecosystem sustainability and climate resilience.

**Keywords:** blue carbon, coastal wetlands, biogeochemistry, machine learning, random forest.

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# Iron Speciation as an Interpretive Framework for Pedochemical Variability in $CO_2$-Degassing Mofette Ecosystems

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## ABSTRACT

Soils influenced by persistent $CO_2$ degassing structures called mofettes, represent complex geochemical environments where redox processes, iron transformations, and ionic chemistry interact across depth and space. However, the role of iron speciation as a lens for interpreting soil geochemical variabilities remains insufficiently understood in such environments. The study investigated the vertical and spatial distribution of iron speciation and its interaction to various soil properties across five mofette sites grounded on the hypothesis of whether the variability in soil properties can be systematically interpreted through which iron is transformed.

A total of 24 soil samples were analyzed for basic soil physical and chemical properties, and iron fractions including ammonium oxalate–extractable iron (amorphous iron or Feo), and pyrophosphate-extractable iron (organically-bound iron or Fep). ANOVA, multivariate techniques, correlation analyses, and linear regression analyses were applied to assess depth trends, site effects, and interrelationships among variables. The soil organic carbon (SOC) was observed to decline significantly with depth ($r \approx -0.50$, $p < 0.05$), while several variables exhibited no depth trends. Base cations, pH, EC, and iron indices showed strong site-specific variability ($p < 0.01$), indicating distinct site-specific pedochemical environments. Correlation analysis demonstrated strong positive association between Fep and SOC, in contrast Feo exhibited no significant associations with SOC.

Principal Component Analysis affirmed closer linkage between organically-complexed iron and SOC. PCA revealed that Fep loaded with SOC and Nitrogen along a dominant organic-associated axis, while Feo, EC, and exchangeable cations clustered along a separate geochemical axis. This highlighted a partial decoupling between redox-sensitive iron pools and SOC storage.

In general, the findings indicate that iron speciation provides a useful interpretive framework for understanding pedochemical variabilities among the studied soils surrounding mofettes, rather than acting as a single controlling mechanism for SOC accumulation. The results also emphasized the importance of accounting the spatial heterogeneity and site-specific geochemical conditions when assessing Fe interactions in redox-affected soils.

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# Recovery of wetland soil function under passive and active hydrological restoration: evidence from multi-decadal spectral indicators

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**ABSTRACT**

Globally, wetland restoration is increasingly being promoted as a nature-based solution or passive recovery for climate mitigation and biodiversity recovery (Schuster et al, 2025); however, evidence linking active human management actions to recovery of soil function at landscape scales often remains limited (Stirling et al, 2020). We assess long-term recovery of wetland soil moisture and surface condition following both passive and active hydrological restoration in degraded peat-forming wetlands in southern Australia, using a 38-year Landsat time series (1987–2025) and adjacent undisturbed wetlands as functional References sites.

In a wetland where grazing exclusion was implemented in approx. 2015 without hydrological engineering, we evaluate changes in surface wetness, organic matter exposure, and hydrological behaviour from trajectory analyses of: vegetation greenness (NDVI), moisture indices (NDMI), near-infrared reflectance (NIR), shortwave infrared reflectance (SWIR1/2), and derived wet-fraction metrics. Prior to fencing, the wetland treatment exhibited persistently lower NDMI, higher SWIR reflectance, reduced wet fraction, and greater interannual variability relative to the References wetland, consistent with drier, oxidised soil conditions under chronic grazing pressure. Following grazing exclusion, all indicators show a rapid and sustained shift toward the References state, with NDMI and wet fraction converging within 3-5 years and SWIR reflectance declining to levels indicative of darker, wetter, and more organic-like surfaces.

A second wetland provides independent evidence of active restoration effects following drain backfilling completed in May 2022. Paired-zone spectral analyses demonstrate a clear step-change in NDMI, increased NIR reflectance, and reduced SWIR reflectance within the re-wetted peaty wetland, contrasting with simultaneous drying trends in adjacent undisturbed peat areas. This divergence indicates localised re-establishment of saturated peat conditions attributable to drain infilling rather than regional climatic forcing.

Rainfall-normalised anomaly analyses across both wetlands demonstrates that post-restoration improvements cannot be attributed solely to climatic variability, and that rehabilitating wetlands demonstrate enhanced moisture retention and resilience. These results indicate functional recovery of wetland soil hydrology and surface organic matter condition under both passive and active management interventions. Our findings demonstrate the utility of multi-decadal remote sensing as an integrated proxy for wetland soil biogeochemical function and provide robust low-cost lines of evidence that grazing exclusion and drain backfilling can restore key soil-mediated ecosystem services-including soil biochemistry, carbon retention, moisture buffering, and climate resilience-under contemporary drying pressure.

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Schuster et al (2025)

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# Vertical Heterogeneity of Soil Arsenic Distribution and Its Relationship with Iron-Manganese Minerals Geochemical Barrier Combined with Microbial Effects

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## ABSTRACT

Arsenic (As) in paddy fields is a significant environmental and health concern. While previous research extensively investigated As dynamics in surface soil, the accumulation of As in the subsoil layer, particularly in an Fe-Mn accumulation layer, remains unexplored. This study aimed to illustrate the heterogeneity of As and its relationship with accumulated Fe-Mn forming geochemical barrier, as well as soil Eh, pH and microbial effects during the formation process.

In this study, paddy soils (Inceptisol) were sampled at three different depths (0-10, 10-20, and 20-30 cm). As-Fe-Mn concentrations were measured in soil solutions and ammonium oxalate (AO), dithionite-citrate-bicarbonate (DCB), and strong acid extractions. The results showed that DCB extractable As concentration in the 10-20 cm soil (278.3±2.8mg/kg) was over 30-fold higher than that in the 0-10 cm soil (8.5±6.8mg/kg), correlating with a higher Fe-Mn concentration. Spectroscopic analyses demonstrated that the distribution of As in soil particles is closely associated with Fe-Mn distribution and suggested possible mineral transformation. The Fe-Mn mineral distribution in soil pore water suggested that hydrodynamic processes played a significant role in the formation of potential As-adsorption Fe-Mn oxides. Adsorption experiments demonstrated that subsoils had a higher As binding and buffering capacity (1403 and 1243 mg/kg) than surface soil (891 and 167 mg/kg).

To clarify possible biogeochemical dynamics triggering this heterogeneous distribution in the vertical soil layer, we performed soil column experiments under flooded situations. From 5 cm, 10 cm, 15 cm and 20 cm depths of soil, we measured Eh and pH in situ and collected soil solutions and soil samples for elements and microbial analysis. During incubation, Eh generally decreased, although the 20 cm layer consistently maintained higher Eh than 5cm layer likely due to unsaturation. This Eh gradient affected soil solution As, Fe and Mn concentrations which were higher in the 5cm and 10 cm layer than 15 cm and 20 cm soil layer. This suggested a higher reduction rate in the surface layer, possible leaching to the subsurface layer and a refixation in the lower layer. The microbial analysis showed significant relationships among microbial communities and soil Eh, pH and soil depth, which resulted in corresponding changes in sequential extraction fractions of As, Fe and Mn elements. Overall, the pronounced vertical heterogeneity of arsenic distribution can be attributed to the combined effects of redox-driven mineral transformations, hydrological transport, and microbially mediated biogeochemical processes.

These findings provided additional evidence for Fe-Mn mineral bound As accumulation in lower soil layer and the possible mechanisms behind. Our experimental results suggested the potential for lower soil layers to retain arsenic by Fe-Mn oxides in limiting arsenic mobility, thereby alleviating the environmental risks associated with arsenic pollution.

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# Coupled effects of human activities and river–Lake interactions evolution alter sources and fate of sedimentary organic carbon in a typical river–Lake system

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**ABSTRACT**

Interconnected river–lake systems record sedimentary organic carbon (OCsed) dynamics and watershed environmental changes, providing valuable information for global carbon budgets and watershed management. However, owing to the evolving river–lake interactions under global change, monitoring OCsed is difficult, thereby impeding the understanding of OCsed transport and fate. This study provided new insights into the dynamical mechanisms of OCsed in a typical river–lake system consisting of Dongting Lake and its seven inlet/ outlet rivers (the three inlets of the Yangtze River and four tributaries) over the last century using stable isotope tracing and quantified the influences of climate change and human activities on OCsed. Results indicated that exogenous OC dominated the OCsed in the lake (58.2 %–89.0 %) and was lower in the west than in the east due to the differences in the material inputs and depositional conditions within the lake. Temporally, the distribution patterns of OCsed sources mainly responded to human activities in the basin rather than to climate change. Before 2005, the Yangtze River contributed the most OCsed (53.5 %–74.6 %), attributed to the high-intensity land use changes (path coefficient ($r\partial$): 0.48, p-value < 0.01) and agriculture-industry activities ($r\partial$: 0.44, p-value < 0.001) in the Yangtze River basin that increased soil erosion. After 2005, a large amount of Yangtze River OC was intercepted by the Three Gorges Dam, altering the OC exchange in the river–lake system and shifting OCsed dominance to the four tributaries (52.2 %–63.8 %). These findings highlight the active response of OCsed to the river–lake interaction evolution and anthropogenic control, providing critical information for regulating watershed management behavior under global change.

# Redox processes of particular organic matter in mediating carbon emissions in peatlands

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**ABSTRACT**

Particulate organic matter (POM) has been proposed as an important reversible electron acceptor that can suppress methane ($CH_4$) emissions in peatlands. However, direct evidence explaining how the redox behavior of POM alters carbon mineralization pathways remains limited. In this study, we conducted a periodic redox-cycling experiment to monitor changes in the electron-accepting capacity of POM ($EAC_{POM}$) and to link these dynamics to carbon emissions in peatland soils. During anaerobic phases, POM respiration caused a lag time of methanogenic phase, effectively diverting carbon flow from $CH_4$ to $CO_2$ emissions. In contrast, aerobic phases were characterized by a pronounced pulse of $CO_2$ release. Follow-up experiments demonstrated that oxidation of reduced POM generated hydroxyl radicals, which strongly promoted oxidative transformations of organic matter. This process notably enhanced phenol oxidase activity and led to substantial abiotic $CO_2$ production during POM oxidation. Overall, our findings reveal a double-edged role of POM in peatland carbon cycling. While POM reduction can suppress $CH_4$ emissions under anoxic conditions, its re-oxidation stimulates organic matter decomposition, particularly lignin degradation, which potentially weakened the "enzymatic latch" in peatlands.

**Key words:** Peatland; redox of POM; $CH_4$; hydroxyl radicals

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# The application of liquid soil activator increased the activity of soil microbiota and enhanced the degradation of straw and plant growth in two different field locations

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**ABSTRACT**

Crop residues represent as valuable reservoir of organic matter for sustaining soil health and fertility. Applying decomposition agents for straw degradation is a useful solution to avoid the adverse effect of traditional management which causes and increases the greenhouse gas emission and air pollution. However, the mechanism of applying the decomposition agent or solution on the soil environment is not fully studied yet. This study investigated the effects of application of a liquid soil activator (LSA) on soil microbial activity and straw decomposition level in 2 fields located in Germany and Serbia. The results showed that the application of LSA increased the abundance of several geniuses involved either directly or indirectly involved in straw degradation. The abundance of microbiota showed different trends in both locations. While in German filed, application of LSA increased the abundance of direct bacterial involved in straw degradation, in Serbia most of the changes belonged to direct funguses. The enhanced abundance of different microorganisms induced by LSA application led to a significant increase in straw degradation under both filed conditions. These findings provide new insights into the role of endogenous application of decomposition agents in straw residue management, highlighting their potential to improve soil health, fertility, and overall soil environment.

**Key words:** Soil biology, soil health, Climate Resilient and plant residue

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# Impacts of soil biostimulants on 'Valencia' sweet orange performance on Flatwoods and Ridge soils in Florida

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**ABSTRACT**

Huanglongbing (HLB) disrupts citrus productivity by reducing fibrous roots early before disease progression, weakening nutrient and water uptake in citrus production. Soil-centered strategies that utilize soil biostimulants may restore the root-soil interface, enhance fruiting, and mitigate pathogen pressure. The objective of this study is to evaluate biostimulants [CitruSaver1(CS1), CitruSaver2 (CS2)], and beneficial microbes (BM) alone and combined (CS2+BM) on the performance of 'Valencia' [Citrus sinensis (L.) Osb.] across two Florida groves differing in soil characteristics and management practices: Wauchula (Flatwoods) and Fort Meade (Ridge). The study was laid in a randomized complete block design with five treatments replicated four times: CS1, CS2, CS2 + BM, BM, and Control. We summarized current harvest weight per plot, Quantitative Polymerase Chain Reaction qPCR cycle threshold Ct values (CLas), juice quality, and fruit drop counts. In Wauchula average yield, CS1 and CS2+BM slightly exceeded CS2 and the Control. In Fort Meade, fruit yields were lower overall, with CS1 highest, followed by CS2. CS2+BM was similar to BM. Wauchula showed slightly higher °Brix (9.94) than Fort Meade (9.53) with comparable ratios (13–13.5). Average fruit drop counts were similar (Wauchula 2.30; Fort Meade 2.05 per sampled unit). Wauchula demonstrated a more precise treatment separation, with CS2 and BM performing well in terms of yield. In contrast, Fort Meade responses were more variable, with CS2 showing higher yield but no clear advantage for BM in Ct values. In Wauchula, CS2 and CS2+BM yielded up to 8% higher fruit mass, indicating reduced pathogen load. Fort Meade responses were smaller but showed improved nutrient retention and stability of juice quality. Biostimulants can improve root-zone efficiency, nutrient-use balance, and soil carbon retention, supporting environmental quality in HLB-endemic citrus systems. Long-term adoption is expected to reduce chemical inputs, improve soil-water interactions, and mitigate nutrient runoff from Florida's citrus landscapes.

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# A Niche-Based Approach of Endemic Cyanobacteria in Soil and Water Conservation in Saline Soils

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**ABSTRACT**

Preventing land degradation and restoring degraded and saline lands is vital for biodiversity conservation, ecosystem services, and human well-being, and is a crucial approach for ensuring food security and sustainable development. Given the detrimental effects of salinity and soil erosion, as well as the consequent soil–water losses, and considering limitations such as high costs, scarcity of raw materials, instability, temporariness, and the environmental drawbacks of commonly used amendments and stabilizers for erosion control, as well as the initial formation steps and the improvement of surface runoff components at the slope, the necessity arises to employ methods with practical, durable, and biological efficiency for controlling soil loss and generating surface runoff in highly saline and alkaline soils. Despite the approved role of biotechnological interventions in mitigating soil and water loss, soil cyanobacteria inoculation to reduce soil degradation in saline soils has not yet received attention. This study aims to evaluate the effect of direct inoculation of soil microorganisms using a surface broadcasting method on soil, through extraction, identification, selection of effective soil cyanobacteria for soil and water conservation, and purification and propagation of these cyanobacteria in bulk volume for planned deployment. Native cyanobacteria from the study area's soil microbial repository were identified, selected, purified, and cultured, and then inoculated on the plots in three replicates. Research findings showed that the volume of runoff produced under simulated rainfall with an intensity of 70 mm $h^{-1}$ for 30 min, after about 60 days of inoculation, in the soil treatment with low salinity and 10% slope, and in the soil treatment with high salinity and 5% slope, the inoculated cyanobacteria reduced soil loss by 60.54 and 32.83%, respectively, while runoff volumes were reduced by 7 and 16 times, with the reductions being statistically significant ($p<0.001$) compared to the control treatment. The results of this study represent a substantial step toward achieving a durable approach in research and management actions for erosion control and the improvement of surface runoff components, thereby preventing the salinization of saline soils and related areas, offering hope for the future of soil conservation.

**Acknowledgments**

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# A SWEET Challenge: Less Sugar for Rhizospheric Microbiome Under the Successive Wheat Rotation

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**ABSTRACT**

Plants adapt to stress conditions by regulating root exudates, which sustain rhizospheric microbial growth and suppress soil-borne pathogens. Soil microbial communities are key regulators of ecosystem functions, driving carbon and nutrient cycling critical for plant productivity. Root exudates, particularly glucose, play a central role in shaping microbial community dynamics and rhizosphere biochemical processes. However, how successive wheat cultivation affects glucose exudation and its downstream effects on microbial activity remains unresolved. In this study, we hypothesized that continuous wheat cropping reduces glucose release, thereby diminishing microbial biomass, activity, and function. We employed optimized *in situ* glucose imaging in root windows installed in field-grown first (W1) and third (W3) wheat crops following break crops. This integrative approach combined spatial glucose mapping with measurements of microbial respiration, enzyme kinetics, and SWEET sugar transporter gene expression in root and leaf tissues. Glucose release hotspots declined by 17.7% in W3 compared to W1, with only 1.35% of the total soil surface showing detectable glucose release in W3. Concurrently, SWEET1a orthologue expression was significantly upregulated in W3, while microbial biomass in the W1 rhizosphere was nearly five times higher than in W3. Enzyme assays revealed significantly higher β-glucosidase $V_{max}$ values in W1, indicating stronger carbon acquisition potential. Gene expression analysis revealed significant upregulation of SWEET1a orthologous genes in W3 roots, suggesting increased demand for energy and carbon for nutrient uptake. In contrast, SWEET13 and SWEET2 orthologous genes were downregulated in W3, indicating shifts in resource allocation. These findings suggest that reduced glucose exudation and altered SWEET gene expression reflect adaptive plant strategies under continuous cultivation, possibly to limit opportunistic pathogens. This study provides novel insights into how continuous wheat cultivation reshapes rhizosphere interactions by altering root exudation, microbial dynamics, gene regulation, and enzyme activity. Moreover, it highlights the utility of *in situ* glucose imaging for advancing our understanding of plant–soil–microbe interactions in agroecosystems.

**Acknowledgments**

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# Shrub-Crop Microbiome and Mycorrhizae Hyphal Interactions: A Novel Rhizosphere Alliance to Mitigate Drought and Promote Beneficial Microorganisms in the Sahel

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**ABSTRACT**

The Sahel is a vulnerable semi-arid environment, with degraded soils where the majority, subsistence farmers routinely face in-season drought and declining crop productivity. Our development of the Optimized Shrub-intercropping System (OSS) with 2 indigenous shrubs *Guiera senegalensis* and *Pilio reticulatum* at elevated densities (~1500) with annual incorporation of coppiced residue - addresses this challenge by increasing soil quality and microbial diversity, performing hydraulic lift (HL), and dramatically increasing yields (fig. 1). Recent field and growth chamber research of OSS will be presented that provides evidence for hydrological and microbiome mechanisms for these positive responses on pearl millet (*Pennisetum glaucum*). A simulated drought field study using deuterium ($D_2O$) as a tracer (applied to shrub roots at 1 m depth) detected a δD signal of > 300‰ increase over background levels in shrub-associated millet tissue; confirming HLed water was transferred to millet. Importantly the +OSS enabled millet to produce a harvestable yield in spite of the 41-day in-season drought, which did not occur in -OSS. Using mesocosms (hydrophobic 36 µm mesh allowing only mycorrhizal hyphae penetration) planted to millet, showed that millet in unturned mesocosms were labeled with $D_2O$ and had much greater tillering/plant biomass than turned microcosms, indicating a common mycorrhizal hyphal network (CMN) connected shrub roots with millet roots. Supporting the role of CMN was greater arbuscular mycorrhizal fungi (AMF) colonization in millet roots and FAME-AMF abundance in shrub over non-shrub soil. Another growth chamber study of early season drought was conducted to remove hydraulic lift as factor and isolate the effect of OSS on soil quality and the microbiome. Microbial metagenomic sequencing showed that shrubs enriched several plant-growth promoting taxa in millet rhizosphere soil (Fig. 2). These organisms have properties such as disease suppression, plant hormone production, and mobilization of nutrients (via hydrolytic enzyme or organic acids). We conclude that shrubs operate as a natural microbial repository that "inoculates" adjacent crop roots; directly reducing drought with CMN "bioirrigating" and by promoting *beneficial microorganisms that are known to improve plant growth and reduce water stress in crops*. Recent findings of pilot testing OSS in farmers' fields in Senegal will also be presented. OSS is appropriate for small holder farmers of the Sahel as the shrubs are a local resource, they are already familiar with.

**Keywords:** microbiome, drought mitigation, Sahel, shrub intercropping

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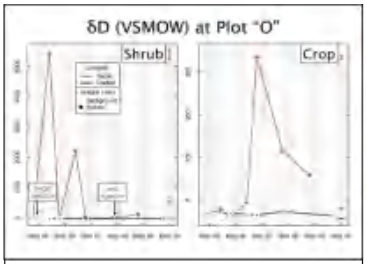
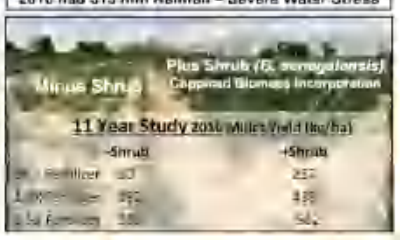



Fig. 2 Uptake of deuterium, into leaves of *G. senegalensis* shrub and millet plants, applied to shrub roots during a simulated in-season drought experiment, near Thies, Senegal.



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# Tradeoffs between microbial life-history strategies drive soil carbon cycling during revegetation in karst ecosystems: A metagenomic perspective

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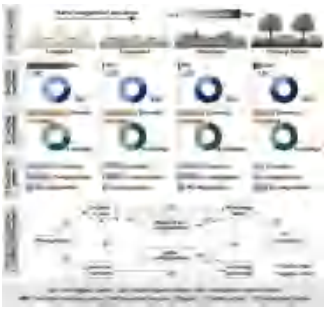
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## ABSTRACT

Revegetation strongly influences the dynamics of soil organic carbon (SOC) and microbial communities. While microbial communities are known to drive carbon (C) cycling, the specific traits responsible for C stabilization and mineralization during the revegetation of degraded karst ecosystems are not well understood. This study used a combination of metagenomic and instrumental methods to investigate variations in soil physicochemical properties, organic C fractions, C-cycle microbial community traits (diversity, life strategies, and co-occurrence patterns), and C-cycling (fixation and degradation) genes across four karst ecosystems representing a revegetation chronosequence encompassing cropland, grassland, shrubland, and primary forest. Our findings demonstrated that revegetation increased total SOC and recalcitrant OC (ROC) contents, while it decreased dissolved inorganic nitrogen (DIN) and reduced the ratio of labile OC (LOC) to SOC. This indicates enhanced C pool stabilization and storage, alongside reduced soil nutrient availability. These shifts favored the development of C-cycle microbial communities with low diversity and high proportions of K-strategists, which efficiently utilize recalcitrant C under oligotrophic conditions. Consequently, the increased dominance of K-strategists redirected microbial resource acquisition, manifested in a 29 % decrease in C-fixation gene abundances (rTCA, WL, and DC/4-HB pathways) and a 27 % decrease in genes degrading labile C compounds (starch, hemicellulose, cellulose, and chitin). Conversely, genes involved in degrading recalcitrant C compounds (pectin and lignin) increased by 19 %. Furthermore, the elevated proportion of K-strategists enhanced the complexity and stability of microbial taxonomic and functional networks, potentially strengthening community resilience and nutrient cycling efficiency. These results reveal a causal link between shifts in the soil C pool and nutrient availability during revegetation and the subsequent reshaping of C-cycling microbial communities. Such restructured communities, in turn, drive the expression of genes associated with C stabilization and mineralization, thereby impacting the soil C pool. This study provides mechanistic insights into microbial-mediated biochemical processes governing soil C decomposition and stabilization in karst ecosystems, offering critical guidance for ecological restoration in these degraded and fragile regions.

**Acknowledgments**

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**Graphical ABSTRACT**

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# Rice aluminum resistance facilitated by bacterial modification of root cell wall in acidic soil

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**ABSTRACT**

The root cell wall is the frontline defense against aluminium toxicity in acidic soil. How rhizosphere microbes affect responses ofthe root cell wall to aluminium stress has not been explored. A previous study showed that an aluminium-tolerant synthetic microbial community (SynCom) was capable of assisting rice growth and production in acidic soils. In this study, we proceeded to examine the association between microbial inoculation and cell wall composition and found that xyloglucan endotransglucosylase (XET) activity increased, leading to modifications in xyloglucan and reduced aluminium accumulation in the roots of an aluminium-sensitive rice mutant. Multiomics profiling revealed that XET activity is regulated by SynCom through the provision of a precursor of brassinosteroids, which activated the plant brassinosteroid pathway. Furthermore, SynCom inoculation promoted the growth of both indica cultivars and japonica cultivars rice plants in the field under aluminium stress by restoring aluminum-induced cell wall modifications. Our findings highlight a sustainable approach to utilizing acidic soils by inoculating SynCom to rescue XET activity and reduce aluminium accumulation in the cell wall (Fig.1).

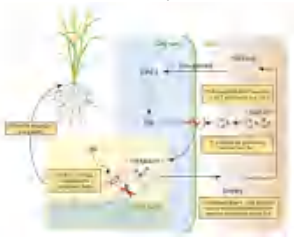


**Fig.1** A schematic model illustrating the effects of SynCom on rice root cell wall modification in acidic soils. (1) The activity ofthe XET enzyme in plants growing in acidic soils is inhibited, leading to the accumulation of aluminium (Al) within the cell wall, which consequently hinders the growth of roots. (2) SynCom releases MVA to enhance the synthesis of BR, including DWF1, in rice roots. BR then upregulates XET activity in the root cell wall, leading to the truncation of the XyG chain, and its components, such as glucan (G), can be released into the rhizosphere. (3) The microbiome may subsequently obtain carbon sources from the root cell wall and reduce aluminium binding to the root cell wall. (4) This process ultimately alleviates soil aluminium toxicity and promotes root cell expansion and growth.

**Acknowledgments**

The authors would like to thank Dr. Jianbo Fan, Dr. Ming Liu, Dr. Xiaoli Liu, and Ling Chen from the Yingtan Agroecosystem Field Experiment Station of the Chinese Academy of Sciences for field experiment management and sampling assistance. The authors received fundings from National Natural Science Foundation of China (42377121, 42230711), National Key R&D Program of China (2021YFD1900400), Strategic Priority Research Program of the Chinese Academy of Sciences (XDA24020104), Innovation Program of Institute of Soil Science (ISSASIP2201) and Youth Innovation Promotion Association of Chinese Academy of Sciences (2016284).

# Methanotrophic activity as a driver of soil carbon cycling in agricultural soils

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## ABSTRACT

Methanotrophic bacteria are active in agricultural soils under different land uses. By oxidizing methane ($CH_4$) to carbon dioxide ($CO_2$) and water, they participate in the carbon (C) cycle. Soil methanotrophy helps lower atmospheric $CH_4$ levels via high-affinity methanotrophs, while also mitigating $CH_4$ emissions by oxidizing elevated methane concentrations within the soil profile before they reach the atmosphere (low-affinity methanotrophy). Through the oxidation of one of the key greenhouse gases, methanotrophs contribute to the mitigation of climate change.

Agricultural practices, alongside seasonal weather variations, strongly regulate soil $CH_4$ uptake. In arable fields, methanotrophic activity is often reduced or inhibited by regular nitrogen fertilization. On grasslands, excessive livestock grazing frequently increases soil compaction, reducing oxygen availability and lowering the capacity to oxidize $CH_4$. As a result, soils under pastures may periodically even emit $CH_4$, whereas mown grasslands typically act as a $CH_4$ sink. In this context, agroforestry systems represent a beneficial practice with the potential to improve soil health and enhance methanotrophic activity and C storage.

We conduct regular measurements of greenhouse gas emissions using the chamber method, combined with assessments of soil physicochemical parameters in pasture and arable fields, including the influence of trees. We will demonstrate how these parameters change seasonally and how they regulate atmospheric $CH_4$ uptake (high-affinity methanotrophy) depending on land use. The conducted research provides quantitative data that will be used for the validation and calibration of the MODASYS (Model for Decision-making in Agri-Environmental Systems) model, developed within the project and operating at the farm level.

Regular field measurements of soil methanotrophic activity provide valuable data on C cycling in agroecosystems, which is particularly important in the context of ongoing climate change and implementation of mitigation practices.

**Acknowledgments**

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# Combined Microbial Inoculation and Reduced Inorganic Fertilization Enhances Diversity and Functionality in Potato Rhizosphere Microbiome at Field Scale

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## ABSTRACT

Intensive potato farming heavily relies on mineral fertilizers, which can be detrimental to the environment. Microbial inoculants emerge as a sustainable alternative to such fertilizers due to their potential to improve nutrient availability and plant health. Nevertheless, their effect on the potato rhizosphere and tuberosphere requires further elucidation. A field experiment was conducted in Southeast Spain on potato using a randomized block design involving four fertilization treatments: conventional mineral fertilization (F100); 50% fertilization reduction (F50); and F50 combined with two distinct microbial inoculants (F50+BA, containing *Azospirillum, Bacillus*, and *Pseudomonas*; and F50+BAFU, containing *Azotobacter, Bacillus*, and non-mycorrhizal fungi). Soil samples from the bulk, rhizosphere, and tuberosphere were collected at four key growth stages: pre-planting, pre-inoculation, post-inoculation, and at harvest. Microbial community composition and diversity were assessed using sequencing data and estimated absolute abundance. The functional potential of the soil microbiome was evaluated by quantifying key genes involved in carbon and nitrogen biogeochemical cycles via quantitative PCR. In the post-inoculation stage, the estimated absolute abundance of potential pathogenic fungi such as *Neocosmospora*, *Botryotrichum*, and *Gibellulopsis* was significantly decreased in the F50+BAFU and F50+BA treatments compared to the F50 treatment, which showed the highest estimated absolute abundance values ($1.48\times10^5$, $1.20\times10^6$, and $6.87\times10^5$ copies $g^{-1}$ soil, respectively) ($p$-value < 0.05). Shannon diversity significantly varied across plant growth stages and soil compartments ($p$-value < 0.001), with the tuberosphere generally exhibiting the highest richness. Notably, during the post-inoculation period, diversity was significantly higher in the F50+BA treatment than in F100 ($p$-value < 0.05), indicating a positive effect of microbial inoculation under reduced fertilization. By normalizing functional gene abundance to total microbial biomass (gene/16S rRNA ratio) during the post-inoculation period, we observed not only a quantitative increase but also evidence of a treatment-driven functional enrichment, as in the F50+BAFU and F50+BA treatments, that significantly increased the abundances of key nitrogen cycling genes, such as *nifH* (0.09 and 0.06 copies $g^{-1}$ soil in April, respectively) and *nirK* (0.008 and 0.011 copies $g^{-1}$ soil in April, respectively), as well as gene GH7 (0.012 copies $g^{-1}$ soil in May), compared to the F100 and F50 treatments ($p$-value < 0.05). Microbial inoculants offer a promising strategy for reducing chemical fertilizer inputs in semi-arid potato cultivation by enhancing beneficial soil functions, temporarily promoting beneficial microbes, improving nitrogen cycling, and suppressing pathogens, thereby supporting a resilient crop microbiome.

**Acknowledgments**

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# Mycorrhiza Helper Streptomycetes Strains for Combating Phytophthora Blight

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**ABSTRACT**

*Phytophthora* blight caused by the destructive soil-borne oomycete pathogens is extremely difficult to control since it attacks the crops underground. Arbuscular mycorrhizal (AM) fungi could not only antagonize or inhibit soil-borne pathogen growth but also defend host against *Phytophthora* blight. However, due to the long-standing challenge in massive production of AM fungal inocula, the effective utilization of soil indigenous AM fungi has become a more desirable path to be explored. To this day, mycorrhiza helper (MH) bacteria as bioenhancers of AM fungi were rarely reported in combating soil-borne diseases. Therefore, a series of studies were conducted to screen MH streptomycetes strains for suppressing *Phytophthora* blight via greenhouse pot experiment, and to explore their specific and combined effects in inhibiting pathogen growth and benefiting AM symbiosis using plate confrontation test, non-targeted metabolomics and pot trials. Mycorrhizal colonization becoming one major factor influencing *Phytophthora* blight when AM fungus present, and *Streptomyces* tricolor (STr) and *S. tendae* (STe) isolated from the rhizosphere of a healthy individual in a *P. capsici*-infected field were screened as MH strains for combating pepper *Phytophthora* blight, while *Kitasatospora herbaricolor* (KHe) and *K. indigofera* (KIn) isolated from an acidic black soil were screened as MH strains for combating soybean *Phytophthora* blight. On one hand, only STr inhibited *P. capsici* growth, while STe which secreted the bioactive substance called 3'-methoxycoumestrol performed better in promoting the propagation and colonization of AM fungus. On the other hand, both KHe and KIn inhibited *P. sojae* growth, while KIn which secreted petroselinic acid and pinocembrin performed better than KHe in increasing AM fungal abundance and the colonization. Compared with any single inoculation, the combined inoculation of STr and STe or KHe and KIn changed the community structure and increased both abundance and colonization of soil indigenous AM fungi, and further decreased pathogen population and the blight severity, while further increased the fruit yield and total nutrient acquisitions. In addition, mycorrhizal colonization positively correlated to soil AM fungal abundance, diversity indices and the actinomycetes population. Taken together, the combined inoculation of STr+STe and KHe+KIn as synthetic microbiota (SynM) is valuable in the future to enhance AM symbiosis against *Phytophthora* blight.

**Acknowledgments**

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# Leguminous Cover Crops Enhance Soil Microbial Communities and Tea Quality via Rhizosphere Microbiome Modulation

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## ABSTRACT

**Introduction**

Tea rhizosphere microbial communities are central to soil ecosystem services, driving nutrient cycling, organic matter decomposition, and plant stress resilience. This study aimed to determine how leguminous cover crops, specifically soybean (LC-S) and cowpea (LC-C), modulate the tea rhizosphere microbiome, enhance soil health, and improve tea quality, offering a sustainable alternative to monoculture tea cultivation.

**Materials and Methods**

This study was conducted at the "Zhongshanlin Tea Experimental Base Station" and the site featured a more than15 year established plantation of *Camellia sinensis* cv. "*Nanjing Yuhua*" tea. The topsoil layers (0–20 cm depth) in tea gardens are distinguished by a sandy loam texture. After two successive years of leguminous cover cropping, tea rhizosphere soil samples within the space of tea rows (i.e., monoculture tea rows, soybean and cowpea cover cropped tea rows) were obtained from tea plantations by extracting intact root-zone cores (20 $cm^2$ surface area × 30 cm depth) from three randomly selected locations or points in each plot. Rhizosphere soil was separated from the roots through a 10 min manual agitation in 1 L of sterile 0.9% *NaCl* solution. A two-year field experiment compared the effects of soybean and cowpea cover crops with conventional monoculture tea systems. High-throughput *16S rRNA* gene sequencing was employed for metagenomic, and metabolic pathway analyses to assess changes in rhizosphere microbial community structure, functional potential, and impacts on tea biochemical quality.

**Results**

Both legume cover treatments (LC-S, and LC-C) significantly restructured the rhizosphere microbiome compared to monoculture controls. *Acidobacteria*, *Proteobacteria*, and *Actinobacteria* were dominant phyla across all treatments. Key functional genera included *Chujaibacter* (regulating microbial circadian rhythms and soil homeostasis) and *Jatrophihabitans* (cytokinin biosynthesis, auxin response, siderophore production). LC-S uniquely enriched *Firmicutes*, *Mycobacterium*, *Bacillus*, and *Nitrospira*, and upregulated degradation and assimilation pathways (*PWY-7315*, *CENTFERM-PWY*) essential for carbohydrate and aromatic compound metabolism. While, LC-C exclusively enriched *Planctomycetes* and *Cyanobacteria*, and enhanced glycan biosynthesis/degradation pathways (*PWY-5744*, *FUCCAT-PWY*), facilitating glyoxylate assimilation and L-fucose degradation. Additionally, both legume cover crop treatments increased beneficial genera such as *Saccharimonadales*, *Leifsonia*, *Frankiaceae*, *Nocardia*, *Conexibacter*, and *Gordonia*, and elevated nitrogenase and glycoside hydrolase activities, optimizing nitrogen assimilation and nutrient cycling. Moreover, legume cover cropping enhanced the biosynthesis of key tea quality compounds, including theanine, polyphenols, catechins, and aromatic volatiles. LC-S primarily promoted aromatic metabolites and carbohydrates, while LC-C favored polyphenolic compounds like flavonoids. The combined incorporation of these two leguminous cover crops synergistically increased the accumulation of bioactive compounds and free amino acids, significantly improving tea's flavor complexity, aroma intensity, and antioxidant capacity.

**Conclusion**

Leguminous cover crops, particularly soybean and cowpea, effectively restructure rhizosphere microbial communities and enhance metabolic functions, creating a dynamic soil environment that supports both ecosystem services and tea quality improvements. This agro-ecological approach offers a sustainable, economically viable alternative to monoculture, advancing soil health, crop productivity, and the market value of tea.

**Keywords:** Legume cover crops; Tea agroecosystem; Soil microbial diversity; Soil resilience; Soil ecosystem services

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# Global Change and Human Activity on Soil Microbial Community and Metabolism

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**ABSTRACT**

Global climate change, as projected by the IPCC to cause a 1.4–5.8°C global temperature rise by 2100 with even faster warming in ecologically fragile regions like the Qinghai-Tibet Plateau, coupled with increasing human-induced exogenous nutrient inputs, poses significant impacts on soil microbial communities and their regulation of biogeochemical cycles, key processes sustaining soil health, plant growth, and carbon sequestration. Soil microorganisms, which drive nitrogen and phosphorus cycling and mediate organic matter decomposition, are highly sensitive to environmental changes, making it critical to clarify their adaptive mechanisms across distinct vulnerable ecosystems. This study focused on three representative ecosystems (Qinghai-Tibetan Plateau alpine meadows, Tianshan glacier forefields, and Shenzhen mangroves) to explore how global change factors (temperature rise, nutrient addition, sea-level rise) shape microbial community structure, metabolic functions, and carbon cycling processes.

In the Qinghai-Tibet Plateau, a 4-year long-term N/P addition experiment at Haibei Station (3100 m altitude) showed that exogenous nutrients reduced plant species richness by favoring fast-growing grasses/sedges, shifted microbial communities toward eutrophic taxa (e.g., Proteobacteria), and altered metabolic priorities—promoting growth-related biosynthesis (e.g., amino acid metabolism) while inhibiting complex organic matter decomposition (e.g., lipid and aromatic compound metabolism), potentially impairing long-term soil carbon sequestration. For Tianshan glacier forefields spanning 10–120 years of succession, microbial functional succession drove carbon stabilization: autotrophic carbon fixation genes decreased significantly, while decomposition and respiration-related genes increased, with priming effects shifting from positive (young soils, nutrient limitation-induced microbial mining) to negative (mature soils, substrate-preferential utilization reducing organic matter loss). In Shenzhen mangroves, tidal gradients regulated microbial carbon use strategies: high/mid-intertidal zones (HT/MT) exhibited negative priming effects (favoring carbon sequestration) with distinct microbial communities (HT: Pseudomonadota; MT: Chloroflexi), while low-intertidal zones (LT) showed positive priming effects, suggesting future sea-level rise may reduce mangrove soil carbon sink potential.

Collectively, these findings reveal ecosystem-specific microbial adaptive mechanisms to global change, providing critical insights for predicting and mitigating the impacts of climate warming, nutrient enrichment, and sea-level rise on fragile ecosystem functions and carbon cycling.

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# A Novel Strategy for Rapid Discovery of Disease-Suppressive Functional Microbial Consortia Using High-Throughput Microbial Community Synthesis

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**ABSTRACT**

Soil-borne diseases incited by fungal and bacterial pathogens persistently threaten global agricultural production security. Excessive long-term dependence on chemical control measures has resulted in a series of pressing issues, including environmental contamination, evolution of pathogen resistance, and food safety concerns. Consequently, the development of environmentally sustainable biocontrol strategies has emerged as a critical research focus in plant protection. Although the application of beneficial microorganisms and their metabolites demonstrates considerable promise, current biocontrol practices predominantly rely on single-strain formulations, such as *Trichoderma* spp. or *Bacillus subtilis*. These monospecific agents face practical limitations, including functional narrowness and poor colonization capacity, which severely constrain their field efficacy and potential for widespread adoption.

Therefore, this study proposes a novel ecological regulation strategy using microbial communities as holistic units. By screening and constructing stable microbial consortia with functional redundancy and synergistic antimicrobial capabilities, we aim to achieve efficient control of soil-borne diseases. The study selected eight different soil samples and utilized three culture media for continuous subculturing over nine generations, constructing a total of 120 serially passaged microbial consortia. From these, 600 derivative consortia were generated for screening antimicrobial functions. The results showed that approximately 20% of the consortia exhibited inhibitory activity against *Fusarium* spp., *Phytophthora* spp., and *Botrytis cinerea*, among which less than 5% demonstrated strong inhibition (inhibition intensity ≥ 80%). Systematic analysis of the stability of the antimicrobial function revealed dynamic evolutionary characteristics in the inhibitory capacity of the consortia: among the 120 serially passaged consortia, 22 were "fluctuating type" (with fluctuating inhibitory ability), 10 were "from presence to absence type," 7 were "from absence to presence type," while only 6 (5% of the total) were "sustained type" with stable inhibitory function. Further employing single-colony isolation and high-throughput community synthesis techniques, the key functional combinations within the "sustained type" consortia were analyzed and reconstructed. The study found that a synthetic community constructed with *Pantoea agglomerans* and *Serratia* sp. increased the inhibition efficiency against tomato gray mold by 7.3% compared to *Serratia* sp. alone. Mechanistic studies indicated that this synergistic effect originated from a 20% significant increase in siderophore secretion capacity under co-culture conditions, thereby effectively inhibiting pathogen growth through iron competition.

In summary, through the systematic research framework of "functional community discovery—key species analysis—synthetic community construction," this study lays a theoretical and resource foundation for building efficient, stable, and resilient synthetic microbial communities. It holds significant value for promoting the development of agricultural biocontrol technologies toward community-based and intelligent directions.

**Keywords:** Synthetic microbial community, Biological control, Antimicrobial mechanism

# Adaptive Responses of Soil $N_2O$-Reducing Bacteria to Fluctuating $O_2$ Levels

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## ABSTRACT

Nitrous oxide ($N_2O$) is a potent greenhouse gas and a significant contributor to global warming. Agricultural soils represent the largest anthropogenic source of $N_2O$, releasing an estimated 2.7-4.8 Tg $N_2O$ annually into the atmosphere (Zhu et al., 2025). $N_2O$ is primarily produced in soils through microbial processes such as nitrification and denitrification. In denitrification, the nitrous oxide reductase (NosZ), which is encoded by the *nosZ* gene, catalyzes the reduction of $N_2O$ to dinitrogen ($N_2$), serving as the only known biological sink for $N_2O$ in soils (Chapuis-Lardy et al., 2007; Juhanson et al., 2017). The *nosZ* gene is generally recognized as being present in two major clades, *nosZ* I and *nosZ* II, which differ in their gene cluster composition, protein secretion pathways, enzymatic kinetics, taxonomic distribution, and co-occurrence with key genes involved in other denitrification pathways. In situ studies have suggested that the two *nosZ* clades may occupy distinct ecological niches within soil ecosystems (Jones et al., 2013; Liu et al., 2023). Soil oxygen ($O_2$) availability is a critical factor that directly influences the production and reduction of $N_2O$ (Qiu et al., 2024; Song et al., 2019; Wei et al., 2023). Compared to other denitrification genes, *nosZ* is particularly sensitive to $O_2$, with its expression being suppressed in the presence of oxygen. limited studies have investigated the effect of $O_2$ on *nosZ* I- and *nosZ* II-carrying microorganisms (Sennett et al., 2024), and the impact of $O_2$ on these two clades and the underlying mechanisms remain insufficiently explored.

In this study, $N_2O$-reducing microbial communities were enriched from fluvo-aquic soil through serial transfers with $N_2O$ as the electron acceptor under three different oxygen conditions: oxic, hypoxic, and anoxic. The microbial communities in all enrichment cultures were primarily dominated by Proteobacteria, followed by Firmicutes and Bacteroidota. Metagenomic and metatranscriptomic analyses revealed that, compared to *nosZ* I-carrying microbes, *nosZ* II-carrying microbes exhibited greater sensitivity to $O_2$. After assembling and de-redundantly processing the metagenomic data, 57 medium- or high-quality metagenome-assembled genomes (MAGs) were recovered, including 11 *nosZ* I-carrying MAGs and 10 *nosZ* II-carrying MAGs. Functional annotation showed that *nosZ* II-carrying MAGs generally lacked key genes related to reactive oxygen species (ROS) defense and genes encoding terminal oxidases. These findings were corroborated by the detection frequencies of these genes across the 3015 *nosZ* I-carrying bacterial genomes and 5237 *nosZ* II-carrying bacterial genomes in the GTDB database. Our results demonstrate that $O_2$ exerts selective pressure on the two *nosZ* clades due to their differing abilities to adapt to oxygen. This study highlights the crucial role of oxygen tolerance in shaping microbial community dynamics and $N_2O$ emission, with significant implications for accurately predicting $N_2O$ emissions from agricultural soils.

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# Uncovering Potential Lanthanide-Dependent Enzymes in High-Rare-Earth Environments

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## ABSTRACT

Historically, lanthanides (Ln) were regarded primarily as cytotoxic agents. High concentrations of $Ce^{3+}$, for instance, destabilize the outer membrane of Escherichia coli by displacing essential $Ca^{2+}$ and $Mg^{2+}$ ions from lipopolysaccharides, increasing permeability and susceptibility to lysis. Consequently, microorganisms in Ln-rich environments have evolved distinct survival strategies, such as extracellular sequestration via surface phosphate groups and intracellular storage in acidocalcisome-like compartments to mitigate toxicity. However, recent discoveries have shifted this paradigm, establishing lanthanides as essential cofactors for specific methylotrophic bacteria. The discovery of XoxF, a pyrroloquinoline quinone (PQQ)-dependent methanol dehydrogenase (MDH), demonstrated that $Ln^{3+}$ can functionally replace $Ca^{2+}$ in active sites. This substitution leverages the higher charge density and Lewis acidity of lanthanides to enhance coordination flexibility and catalytic efficiency, a phenomenon strictly required for the growth of extremophiles like *Methylacidiphilum fumariolicum* SolV. Despite the comprehensive characterization of MDH, the broader landscape of lanthanide biochemistry remains largely unexplored. To investigate whether other enzymes exploit lanthanides, we performed a computational screen of metagenomic data derived from high-rare-earth mining environments. We focused on sequences containing the canonical calcium-binding EF-hand motif, identifying 534 candidate sequences. We employed AlphaFold2 for structural prediction, Foldseek for functional annotation, and Discovery Studio for molecular docking simulations to evaluate lanthanide binding affinity relative to calcium.Our analysis identified 94 distinct proteins, dominated by signal transduction factors (85%) and metabolic enzymes (8%). Docking results revealed five specific enzymes with a theoretically higher binding affinity for $Ln^{3+}$ than $Ca^{2+}$: phosphatidylserine decarboxylase precursor, transaldolase, glycerol-3-phosphate dehydrogenase, ATPase, and calcium-dependent protein kinase. Additionally, enzymes such as metallo-β-lactamase and $NH_3$-dependent $NAD^+$ synthetase exhibited affinities suggesting potential Ln-substitution via mass action effects in high-Ln backgrounds. These findings significantly expand the potential scope of lanthanide utilization in biological systems. Future work will focus on the spectroscopic characterization of these candidates to validate the impact of lanthanide binding on enzymatic activity and conformational stability.

# Beyond plant diversity: plant productivity responses to extreme drought are linked to arbuscular mycorrhizal fungal diversity

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**ABSTRACT**

Plant and arbuscular mycorrhizal (AM) fungal diversity are both positively linked to ecosystem productivity across diverse ecosystems. However, given their high sensitivity to climate extremes such as extreme drought, the persistence and adaptability of these diversity-productivity relationships under rapid climate changes remain poorly understood. To address this, we established a grassland experiment at two sites with distinct natural plant and AM fungal communities, imposing two contrasting extreme drought regimes (intense and chronic), each exceeding a 20-year recurrence interval based on site-specific precipitation records. We show that AM fungal diversity consistently outperforms plant diversity in predicting plant aboveground/net primary productivity (ANPP/NPP), as well as compositional shifts in plant species productivity, despite pronounced drought sensitivity in both communities. Notably, enhanced drought resistance in plant productivity was primarily associated with the stability of AM fungal richness rather than plant richness, highlighting their mutual dependence under extreme drought. Structural equation modelling confirmed that AM fungal richness buffered drought effects on ANPP, NPP and plant richness, with stronger effects on ANPP and NPP than those of plant richness and soil properties. These results suggest that AM fungal diversity may play a greater role than plant diversity in buffering plant communities against climate extremes. While causality remains to be fully resolved, these findings shed light on the adaptive significance of this ancient symbiont in sustaining ecosystem functioning under rapid climate change.

**Key words:** arbuscular mycorrhizal fungi, soil biodiversity, climate extremes, climate change

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# Phosphogypsum Effects on Soil Microbial Communities Revealed by PLFA Analysis in Arenosol and Meadow Chernosem Soil

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## ABSTRACT

Phosphogypsum (PG), a by-product of phosphoric acid production, is a major industrial waste material (*Hanfeng et al,* 2025). Although it contains valuable nutrients, its agricultural use remains debated due to potential contamination risks. Nevertheless, interest is increasing in its use as a soil amendment, as PG may improve soil chemical properties and influence the soil microbiome, a key factor in soil health. Understanding the effects of PG on soil microbial communities is therefore essential for assessing its suitability for sustainable agriculture.

This study examined PG-induced changes in soil microbial biomass and community composition using phospholipid fatty acid (PLFA) analysis in two contrasting soils: an Arenosol (pH(KCl)=4.92) and a salt-affected, compacted Gleyic Chernozem (pH(KCl)=6.17). A two-year greenhouse pot experiment was conducted, where in the first year, PG was applied at 2 and 10 t $ha^{-1}$, with untreated controls. In the second year, pots were divided to assess either residual effects (no additional PG) or repeated applications (same doses re-applied) of PG. Spring wheat (*Triticum aestivum* L.) was grown in both years. Although the pot experiment covered a two-year period, the present study reports the results obtained in the second year.

Phosphogypsum increased total microbial biomass in both soils. In Chernozem, biomass was generally higher (220.9–301.7 nmol $g^{-1}$), with the lowest values in the control and the greatest increase in the repeated 2 t $ha^{-1}$ PG treatment. In Arenosol, biomass ranged from 157 to 231 nmol $g^{-1}$, with the lowest values in the control and the highest in the 10 t $ha^{-1}$ treatments under both residual and repeated PG addition.

Arbuscular mycorrhizal fungal biomass in Chernozem (10.7–49 nmol $g^{-1}$) increased significantly under all PG treatments, whereas Arenosol values (7.2–10.8 nmol $g^{-1}$) were lower and not significantly affected. Total fungal biomass showed no significant PG-induced change in either soil.

Gram-positive bacteria were more abundant in Arenosol (73.4–99.0 nmol $g^{-1}$) than in Chernozem (43.2–61.5 nmol $g^{-1}$) and showed slight, non-significant increases with PG. Gram-negative bacteria were less abundant in Arenosol (36.2–47.4 nmol $g^{-1}$) and more abundant in Chernozem (43.3–61.5 nmol $g^{-1}$), with no significant effects from PG.

Actinomycetes were more abundant in Chernozem (11.6–14.79 nmol $g^{-1}$) and were significantly increased by PG in the residual 10 t $ha^{-1}$ and repeated 2 t $ha^{-1}$ treatments, while Arenosol showed slightly lower values with no significant change under PG.

The fungal-to-bacterial ratio increased markedly in Chernozem (0.167–0.387 nmol $g^{-1}$) under PG treatments, indicating a shift towards a more fungi-dominated community, whereas Arenosol (0.10–0.17 nmol $g^{-1}$) remained unaffected.

Overall, PG enhanced microbial biomass and, in some cases, beneficial microbial groups, supporting its potential as a soil amendment, although responses varied between soils and microbial components.

**Keywords:** phosphogypsum, PLFA, soil microbial community

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# Machine-Learning-Driven Decoding of Microbial Quinclorac Cometabolic Degradation

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**ABSTRACT**

The paddy-field herbicide Quinclorac (QNC) persists in soil and aquatic systems, accumulates along gradient-driven pathways, and inflicts phytotoxicity on succeeding crops while posing acute threats to aquatic organisms. An efficient and eco-friendly removal technology is therefore urgently needed. Microbial degradation is regarded as the most sustainable solution, however, current studies remain at the stage of strain isolation and phenotypic verification, and a genome-scale consensus on QNC-degradation pathways, key genes and regulatory networks is still lacking.

Here, a high-efficiency QNC-degrader, *Mycolicibacterium* sp. Qt1, was isolated from QNC-contaminated paddy soil and completely removed 50 mg/L QNC within 96 h, markedly reducing its ecotoxicological impact. Metabolite profiling and pathway reconstruction revealed four QNC-degradation routes and several novel intermediates. Machine-learning-driven multi-omics and protein-ligand docking systematically identified the genes and enzymes driving QNC transformation. On this basis, the first genome-scale metabolic model (iQt1) constrained solely by QNC cometabolism was constructed; it unbiasedly scanned genome-wide conditional-essentiality landscapes, pinpointed hidden metabolic nodes that become lethal in the presence of QNC, and quantified the energy/redox-electron competition between the catabolic pathway and central metabolism, thereby exposing the systemic bottleneck responsible for the gap between theoretical and observed degradation rates.

This study provides a panoramic, mechanistic understanding of microbial QNC degradation and offers computable targets and theoretical guidance for the precision bioremediation of Quinclorac-contaminated sites, while pushing the frontiers of environmental microbiology and systems biotechnology.

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# The stem microbiome assists maize in resisting stalk rot

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**ABSTRACT**

The mutualistic symbiosis between plants and their core microbiota plays a crucial role in maintaining plant health and enhancing disease resistance. However, the specific functions and mechanisms through which the phyllosphere microbial community confers protection against pathogen infection remain poorly understood. In this study, we collected 1,410 samples from multiple compartments (including bulk soil, rhizosphere, roots, stems, and seeds) of healthy and stalk rot diseased maize plants across a continental-scale transect spanning 3,317 kilometers in China. Amplicon and metagenomic data analyses revealed that stalk rot disease significantly disrupted the composition of the maize microbiota. Compared to other plant tissues, the integrity and function of the highly conserved stem microbiota were more severely compromised by the pathogen. Continental-scale sample analysis identified 14 bacterial and 26 fungal core taxa within the maize stem microbiota. Inoculation with a synthetic microbial community (SynCom) composed of six core bacterial and six core fungal strains demonstrated that these stem-endophytic microbes effectively alleviated pathogen infection. Strain removal experiments within the SynCom identified the fungus *Penicillium fructuariae-cellae* as a key contributor to disease resistance in the stem microbiota. *P. fructuariae-cellae* broadly inhibits multiple pathogenic fungi through the production of small molecular compounds. This study highlights the untapped potential of often-overlooked stem-endophytic core microbes in enhancing disease resistance and provides a promising strategy for mitigating globally prevalent stalk rot in maize.

# Resistant crops engineer beneficial soil microbial legacies for disease suppression

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**ABSTRACT**

Healthy soils with diverse and beneficial microbiomes are essential for sustainable agriculture and for protecting crops against soil-borne diseases. However, it remains unclear how plant genotypes generate soil microbial legacies and whether these legacies can be leveraged to enhance crop resilience across growing cycles. Using banana varieties differing in Fusarium wilt resistance, we combined soil conditioning, cross-inoculation, microbiome profiling, metabolite assays, and synthetic microbial community (SynCom) experiments to uncover the ecological and mechanistic basis of disease suppression. Soils conditioned by the highly resistant variety created a persistent beneficial legacy that improved the health of the susceptible variety, whereas soils conditioned by the susceptible variety promoted pathogen buildup. Bacterial communities were particularly responsive to legacy effects, while fungal communities were more strongly shaped by varietal identity. Resistant varieties selectively recruited microbial groups with strong pathogen-inhibitory potential, and their growth was stimulated by distinct root-derived metabolites. SynComs designed from these enriched microbial groups effectively reproduced the suppressive effects of resistant-variety microbiomes and significantly reduced pathogen abundance. Supplementation with metabolites characteristic of the resistant variety further enhanced SynCom performance. Together, our findings demonstrate that resistant crops can engineer beneficial soil microbial legacies through targeted recruitment of disease-suppressive microbiomes. This nature-based mechanism offers a promising path for improving soil health, reducing pathogen pressure, and supporting more sustainable and resilient agricultural systems.

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# Long-term soil storage highlights the role of precipitation history in microbial dynamics and $CO_2$ emissions

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**ABSTRACT**

Greenhouse gas emissions (GHG) challenge the modern world and future generations. One possible strategy for climate change mitigation is enhancing soil carbon (C) sequestration by promoting C uptake from the atmosphere and storing it in the form of soil organic matter to reduce increases in atmospheric $CO_2$ concentration. Agricultural soils can store C making them an important component of climate change mitigation strategies. The key to understanding C dynamics in soils is integrating the role of microbial communities since they control net C transformations. In this study, we assessed the potential link between soil organic C (SOC) and soil microbiomes in pasture soils in the South Island of New Zealand and the role of median annual precipitation (MAP) in controlling them.

A total of 48 soil samples were collected from 16 farms across the South Island of New Zealand, spanning a MAP gradient (500-5000 mm per year). Metagenomes and 16S/ITS rRNA profiles were generated from DNA extracted from fresh composite soil samples representing the top 0-10 cm, and for the same samples after air drying for one year. Soils were then used to measure $CO_2$ emissions and assess the Birch Effect after re-wetting.

Significant differences in fungal communities were observed in fresh soils, with strong grouping of sites based on MAP, where sites with < 1000 mm of rain a year clustered separately from higher rainfall areas, but similar clustering was absent for prokaryotes. However, both fungi and prokaryotes demonstrated strong clustering based on MAP after one year of drying. Furthermore, we observed higher $CO_2$ emissions from lower precipitation sites in response to water addition.

Our findings highlight how long-term soil storage provides better insight into microbial community assembly drivers. It suggests that caution with data interpretation is needed to disentangle the role of short-term disturbances (e.g. recent moisture changes) vs long term climactic and geologic drivers (e.g. historical precipitation patterns) of microbial community assembly patterns. The results also indicate that under future climate change scenarios, altered rainfall could lead to significant losses of SOC.

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# Culture-Dependent Bacteriome Analysis Reveals PGPB Candidates for Okra Biopriming under Salinity Stress

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## ABSTRACT

Soil salinity is one of the fastest growing threats to global agriculture, with the FAO 2024 assessment reporting that about 10% of irrigated and rainfed croplands are already salt affected. Climate-driven aridification could expand the affected land surface to 24–32% in the coming decades, with the greatest impacts expected in arid and semi-arid regions. Among crops cultivated in these environments, okra is widely grown yet sensitive to salinity at all growth stages. Salinity suppresses plant growth and reduces soil microbial diversity, limiting key functions that support soil and plant health. While metagenomics offers valuable microbial community profiles, culture-dependent approaches remain necessary to obtain living cultures and evaluate their plant-beneficial traits, particularly for applications such as biopriming. This study aimed to characterize culturable bacteriomes from inland and coastal soils and identify plant growth-promoting bacteria (PGPB) candidate for okra biopriming under salinity. A total of 70 bacterial strains were obtained with serial dilution method from four locations using R2A and LB for inland soils (codes: NTR and FLD) or R2A with 1.5% NaCl and Marine Agar for coastal soils (codes: BEA and OKB). Relative abundance analysis based on 16S rRNA gene sequences showed a distinct genus composition between inland and coastal bacteriomes. *Bacillus* spp. was isolated consistently across all sites, whereas *Pseudomonas* spp. was the second most represented genus in coastal soils but rarely isolated inland. Several genera were site-specific, such as *Stenotrophomonas* in NTR and *Brucella* in OKB. Principal component analysis (PCoA) grouped inland and coastal communities separately, associating BEA with bacteria from genus *Microbacterium*, *Arthrobacter*, and *Metabacillus*, and FLD with genus of *Rossellomorea*, *Pantoea*, *Ralstonia*, and *Acinetobacter*. Functional potential was assessed through four PGP traits relevant to salinity: IAA production, EPS secretion, ACC-deaminase activity, and phosphate solubilization. Eleven strains produced IAA, seven showed ACC activity, thirteen solubilized phosphate, and fourteen secreted EPS. Nine multi-trait strains were subsequently tested for okra biopriming in a factorial completely randomized design using nine bacterial treatments and two salinity levels (0 and 150 mM NaCl) for 25 days, each contained 9 replications. Biopriming with these strains significantly improved okra biomass, particularly under salinity treatment. At 150 mM NaCl, *Rossellomorea marisflavi* FLD31 and *Ralstonia pickettii* FLD34 increased total dry mass from 96.96 mg in the control to 241.24 mg and 196.77 mg respectively. *Rossellomorea marisflavi*, though moderately halophilic, remains poorly studied in plant-microbe-soil interactions. These findings highlight the potential of underexplored soil bacteria to enhance crop performance under saline conditions and emphasize the importance of preserving soil biodiversity.

# Applying wild (NatCom) soil microbiomes to alleviate primary stressors for peas and wheat

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**ABSTRACT**

Soil microbes have closely evolved with plants, and enhance the root acquisition of soil nutrients. Some rhizosphere microbes offer other benefits to plants, such as improving plant's immunity to diseases and tolerance to environmental stresses. Annual crops requiring high-inputs are appear to be degrading soil health, exacerbating the dependence for more chemical inputs to maintain yields profitable. The microbiome rewilding hypothesis posits that plant health can be improved by reinstating the diverse (ancestral) microbes that were lost through domestication and industrialization. In the case of rewilding with soil microbes, this implies the loss that occurred through plant breeding for high-input or overuse of pesticides and fertilizers during the industrialization of agriculture. Evidence is mounting that degraded agriculture fields can be restored, and regain a highly functional soil, if microbiome wilding is implemented (Ramirez-Villacis et al. 2025). We tested the potential of wild soil microbiome inoculation with ancient pea species (e.g. *Pisum fulvum*), field pea cultivars (*P. sativum*); ancient wheat species (e.g. *T. monococcum*), and some old and modern wheat cultivars (*T. aestivum*). Diverse 'wild' rhizosphere soil was collected from native grasslands and pastures and used as a whole-soil community inoculum for growing plants in glasshouse trials. Preliminary results from these proof-of-concept experiments are discussed. For example, pea cultivars had about a 2.5 fold increase in nitrogen-fixing nodules, and tended to have less root rot (likely *Aphanomyces* or *Fusarium*) after growing with the 'wild' soil inoculum. Only under drought, and in ancient wheat were positive responses to the 'wild' soil inoculum found, in comparison to grown in sterile soil. Specifically, with ancient wheat, the 'wild' inoculum produced greater grain yield and improved tolerance to dry and nutrient-poor soil. A second set of experiments using diverse 'wild' soil communities (NatCom *sensu* Darriaut et al. 2025) is currently showing some promise to improve root growth and lower root rot in ancient and modern pea. Follow-up experiments with wheat and a greater domestication gradient are ongoing. More research on 'wild' rhizosphere microbiomes with common annual crops, could improve our understanding of the role of ancestral microbial associations, to improve sustainable agriculture. Harnessing and optimizing 'wild' soil consortia could help reduce the input costs of farmers, while simultaneously improving soil biodiversity and bolstering soil health.

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# The diverse autotrophic communities of mangrove sediments

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**ABSTRACT**

Mangrove forests present a critically important coastal natural ecosystem, playing vital roles in carbon sequestration, biodiversity conservation, wave attenuation, water purification, etc. Despite this, the mechanisms of carbon sink formation in mangroves remain unclear, with a key knowledge gap lying in understanding the microbial communities that drive this process. This study investigated the diversity and composition of benthic autotrophs across varied coastal environments in Guangdong, China, including urban estuaries, industrial bays, mariculture areas, and mangrove coastlines. Using high-throughput sequencing of 16S and 18S rRNA genes, we characterized prokaryotic and eukaryotic autotrophic assemblages and evaluated how anthropogenic activities influence their structure. Results revealed that industrial heavy metals such as Cd and Zn, along with interactions with micro-eukaryotes (e.g., protists, metazoans, and parasites), significantly reshaped autotrophic community organization. Industrial pollution markedly reduced the abundance of both prokaryotic and eukaryotic autotrophs. In contrast, mangrove sediments promoted a distinctive community shift, enriching autotrophic taxa including sulfur-oxidizing bacteria, iron-oxidizing bacteria, and microalgae. This shift suggests a coupling of sulfur and iron cycling with carbon sequestration processes in mangrove ecosystems. Overall, these findings demonstrate that anthropogenic factors alter coastal sediment carbon sequestration capacity by restructuring autotrophic communities, with mangroves playing a mitigating and functionally enriching role.

**Acknowledgments**

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# Response mechanisms of plant-soil nutrients and microorganisms to N:Ca ratio in poplar plantations of Northeast China

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## ABSTRACT

Global nitrogen (N) deposition deposition alters ecosystem nutrient stoichiometry. While N is essential nutrient for plant photosynthesis and calcium (Ca) is structural and regulatory substance in plants, the microbial mechanisms linking N:Ca ratios to plant-soil processes remain largely unexplored. We analyzed ten poplar plantations across 41°53′–48°14′N in Northeast China's Three-North Shelterbelt. We collected poplar leaf samples and soil samples from different soil layers to characterize the distribution of N:Ca ratio across all sites. We further examined correlations between N:Ca ratios and leaf nutrient contents, as well as soil physicochemical properties. Additionally, metagenomic sequencing was used to explore the characteristics and functional potentials of soil microbial communities in sites with distinct N:Ca ratios. The results indicated that soil N:Ca ratio ranged from 0.21 to 0.53 in the 0–20 cm layer and 0.16 to 0.57 in the 20–40 cm layer, increasing significantly along the latitudinal gradient ($p < 0.05$). Total nitrogen (TN), total carbon (TC), exchangeable calcium (ECa), altitude, and total potassium (TK) were identified as the top five key driving factors, cumulatively accounting for 96.1% of total variation. Regression analysis revealed that extremely significant positive correlations of soil N:Ca ratio with TC and TN, extremely significant negative correlation with TK, and a unimodal response to ECa ($p < 0.001$). Meanwhile, poplar leaf N and tissue Ca contents were strongly positively correlated with the N:Ca ratio, whereas leaf C and phosphorus (P) showed significant negative correlation ($p < 0.001$). In terms of soil microbial communities, elevated N:Ca ratio significantly reduced the α-diversity of both bacteria and fungi ($p < 0.05$). Bacterial communities exhibited significant separation across N:Ca ratio gradients, but fungal communities exhibited no significant separation. With respect to functional genes, the abundance of carbon cycle-related genes first increased and then decreased with increasing N:Ca ratio. In nitrogen metabolism, functional gene relative abundances differed by specific function. Additionally, the abundance of calcium signaling related genes significantly decreased with elevated N:Ca ratio. Structural Equation Modeling (SEM) verification confirmed that N:Ca ratio exerted negative regulatory effects on carbon cycling, nitrogen metabolism, and calcium signaling pathways ($p < 0.05$). As atmospheric N deposition intensifies, shifts in N:Ca balance may compromise plant resilience and productivity. By uncovering this overlooked nutrient interaction, our study provides a foundation for optimizing fertilization strategies in forestry to enhance resource efficiency and mitigate the effects of global N deposition.

# The impact of trees on soil microbial biomass and $CO_2$ emissions from fertilized soil

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**ABSTRACT**

Approximately 37% of the Earth's terrestrial surface is used for agricultural purposes, including arable land (33%) and grasslands (67%) [1]. Through microbial and root respiration, these systems consume oxygen and release carbon dioxide ($CO_2$), contributing to global greenhouse-gas emissions. Developing climate-resilient and environmentally sustainable agriculture therefore requires practices that enhance soil health and biodiversity, strengthen microbial functioning, and reduce atmospheric $CO_2$ release - such as maintenance and implementation of agroforestry systems and rational fertilization strategies.

In this context, our study examines how agricultural management and landscape structure shape soil microbiome activity and $CO_2$ emissions. The regular field measurements were carried out to generate quantitative data for validating and calibrating the MODASYS model (Model for Decision-making in Agri-Environmental Systems), under development for estimation of greenhouse-gas emissions at the farm scale. Soil $CO_2$ fluxes were determined using the dynamic chamber method with simultaneous soil condition testing and sampling for microbial biomass carbon (C) assessment using the Substrate-Induced Respiration (SIR) technique.

Results reveal pronounced spatial variability: fertilized plots distant from trees exhibited the highest $CO_2$ fluxes, whereas unfertilized zones near trees showed substantially lower emissions with seasonal changes both soil respiration and microbial biomass C. These patterns are consistent with recent empirical findings confirming that soil microbiomes respond strongly to fertilization regimes, organic amendments, and biogeochemical gradients [2, 3]. Seasonal reductions both in $CO_2$ fluxes and microbial biomass highlight temperature-driven constraints on microbial metabolism further modulated by the presence of trees.

By integrating microbiological indicators with field-scale gas measurements, this study demonstrates how soil microbial communities mediate C cycling under contrasting management conditions. The results reinforce the crucial role of diverse and functional soil microbiomes in supporting climate-resilient agriculture, restoring degraded soils, enhancing C sequestration, and stabilizing ecosystem processes essential for sustainable food production.

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# Reseeding Caragana korshinskii recovers soil microbiome structure but not stability or complexity after eight years in degraded desert steppe

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**ABSTRACT**

Reseeding the legume *Caragana korshinskii,* is an effective strategy to restore the vegetation in degraded desert steppe. Here, we explored the responses of soil environment and microbial communities to desert steppe degradation and *C. korshinskii* reseeding. A typical native-degraded-restored closed-loop system in desert steppe: the natural stage with native *C. korshinskii* (NC), vegetation degradation stage (bare soil) (BS), both vegetation and soil degradation stage (desertified soil) (DS), and restored stage with reseeding *C. korshinskii* aged eight years (RC). The results showed that, within this closed-loop system: 1) Compared to BS, soil degradation (DS) resulted in a 199% increase in sand content ($P < 0.05$), while no difference between RC and NC ($P > 0.05$), indicating restoration of soil texture. 2) The soil microbial structure of RC was similar to that of NC, but based on changes in abundance, it could be divided into communities that increased with the rise in soil sand content (UTC+SPP), decreased due to vegetation degradation and increased soil sand content (FOC+SEC) ($P < 0.05$), and unchanged (UC). 3) Microbial networks showed lower average degree and modularity after reseeding *C. korshinskii* compared to NC. In summary, eight years of vegetation restoration led to the recovery of soil texture and microbial community structure, but not community complexity and stability. The results emphasize the time lag for soil microbiome reconstruction after reseeding *C. korshinskii*, providing novel insight into plant-soil-microbial interactions during the restoration of degraded desert steppe.

Keywords: desert steppe degradation, legume reseeding, soil microbial diversity, soil microbial complexity and stability, soil texture

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# Unraveling the mechanisms of halotolerant plant growth-promoting microbes in saline–alkaline habitats through microbial diversity, functional traits and transcriptomics

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## ABSTRACT

Soil salinization and alkalization severely threaten global agricultural sustainability, affecting approximately 955 million hectares worldwide. Harnessing beneficial soil and plant-associated microbiomes represents a promising strategy for improving crop performance and rehabilitating degraded saline soils. Here, we investigated the diversity, functional potential, and plant growth–promoting mechanisms of endophytic and rhizospheric microbes associated with salt-adapted plants around the extreme saline–alkaline Yuncheng Salt Lake, China.

Using culture-dependent methods, we isolated 175 endophytic strains (4 phyla, 43 genera) and 121 rhizospheric strains (5 phyla, 39 genera). Amplicon-based sequencing revealed much broader diversity, with rhizosphere communities spanning 44 phyla and 108 classes. A high proportion of endophytic bacteria remained taxonomically unclassified, highlighting the substantial novelty of microbial resources in this extreme ecosystem. Functional screening showed that many isolates exhibited multiple plant growth–promoting (PGP) traits, including indole-3-acetic acid production, phosphate solubilization, siderophore and exopolysaccharide synthesis. Functional annotations further revealed widespread stress-adaptive features related to heat shock, UV resistance, oxidative stress defense, and osmotic regulation. Inoculation experiments under salt stress (12 g/kg NaCl) demonstrated that both individual endophytic strains (PG04, LC43, GM11) and a composite microbial consortium (CPDS) significantly enhanced wheat (*Triticum aestivum* L.) seedling growth. Compared with uninoculated controls, shoot height increased by 19.96–25.83% for single strains and by 33.24% for CPDS, while shoot biomass increased by 30.17–36.71% and 60.13%, respectively. CPDS showed the strongest effect, increasing mean shoot height to 167.07 mm and fresh seedling weight to 126.5 mg. Leaf chlorophyll content was significantly elevated by all inoculations, with CPDS and LC43 reaching 2.31 and 2.13 mg/g. Similar growth-promoting effects were observed following rhizospheric microbial inoculation, particularly with strain CUG-104, which markedly increased shoot height, root length, and fresh weight, and enhanced chlorophyll content, proline accumulation, and antioxidant enzyme activities (SOD and CAT).

Transcriptomic analysis of representative treatments (CUG-104 and CPDS) revealed distinct yet complementary mechanisms underlying microbial-mediated salt tolerance. Both treatments activated plant hormone signal transduction and starch and sucrose metabolism. CUG-104 preferentially enriched arginine and proline metabolism, fatty acid elongation, and glycerophospholipid metabolism, contributing to osmotic adjustment and membrane stability. In contrast, CPDS strongly enhanced photosynthesis, Calvin cycle carbon fixation, zeatin biosynthesis, protein processing in the endoplasmic reticulum, and reactive oxygen species detoxification, thereby promoting biomass accumulation and cellular homeostasis under saline stress.

Overall, microbes from salt-adapted plants employ synergistic and strain-specific strategies to enhance plant salt tolerance and growth. This study provides novel microbial resources and mechanistic insights for developing bio-inoculants to improve crop resilience and support sustainable saline soil rehabilitation.

# Tracing the dynamic life story of soil microbial hotspots

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## ABSTRACT

Soil microhabitats are dynamic sites of microbial hotspots with intense biological activity that disproportionately drive organic matter (OM) turnover. Ecological transitions of microhabitats can alter their biological traits, and consequently, affect OM formation and decomposition. However, a mechanistic understanding of how microbial function and community assembly of microhabitats shift through ecological succession remains unclear. Since formation and decomposition of OM are largely oxidative processes, we used *in-situ* zymography of oxidative enzymes (peroxidases and phenol oxidases) to visualize their spatial activity as an indicator of OM turnover. Combined with planar optodes for $CO_2$ efflux, microscopic imaging to verify biopore reuse by new roots, and microbial analyses (PLFAs and substrate-induced growth respiration), we traced the life story of microbial hotspots from a maize rhizosphere to its root-detritusphere, then to bare biopores, and finally to biopores reused by lentil roots.

The maize rhizosphere was characterized by high $CO_2$ efflux hotspots (12.2%) derived from root and rhizomicrobial respiration, but low oxidative activity hotspots (0.31%), supporting the dominance of fast-growing, copiotrophic microorganisms such as Gram-negative bacteria. This pattern shifted dramatically in the root-detritusphere, where the oxidative hotspots increased 7-fold (to 2.25%), driven primarily by saprophytic fungi decomposing fresh necromass. At the same time, the concentrated input of labile carbon from decaying roots sustained a high abundance of Gram-negative bacteria, thereby maintaining microbial growth rate comparable to that in the maize rhizosphere. However, $CO_2$ efflux declined by 25% relative to the maize rhizosphere, indicating a shift from autotrophic to heterotrophic respiration. As decomposition of root residues progressed, the reduced availability of labile carbons likely constrained microbial growth in bare biopores, as reflected by lower oxidative activity and $CO_2$ efflux hotspots compared to the root-detritusphere. This pattern indicates constrained decomposition of recalcitrant residues, concurrent with a microbial community shift towards slow-growing Gram-positive bacteria and actinobacteria. Reoccupation by lentil roots revitalized hotspots, yielding the highest oxidative activity (3.15%) and $CO_2$ efflux (13.5%) hotspots, reactivating fast-growing communities via positive rhizosphere priming.

We conclude that microhabitat succession may affect OM formation and decomposition by shifting the balance between oxidative and respiratory decomposition through the restructuring microbial community and enzyme deployment in space and time. These findings underscore that management practices that promote root-derived inputs and biopore reuse, such as reduced tillage and crop rotation, can sustain microbial hotspots and enzymatic activity, thereby enhancing nutrient cycling while potentially stabilizing OM in carbon-limited microhabitats.

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# The Regulatory Role of Rhizosphere Microorganisms in Tobacco Resistance to Black Shank Disease

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**ABSTRACT**

Plant roots assemble taxonomically and functionally diverse microbial consortia that constitute a "second genome" essential for host health. Yet, how plants exploit rhizosphere microbiota to enhance disease resistance remains insufficiently understood. Here, using the Solanaceae crop *Nicotiana tabacum*, we dissect how rhizosphere microbial communities modulate host immunity against black shank of tobacco (*Phytophthora nicotianae*). Susceptible (XHJ) and resistant (BH) cultivars were grown in soils differing in microbial complexity, followed by pathogen inoculation during the seedling stage. Integrated phenotyping, expression profiling of defense-related hormone pathways, and 16S rRNA–based microbial community analyses were performed.Plants grown in field soil exhibited markedly reduced disease severity compared with those in sterile soil, indicating a protective role of native microbiota. Root-split and soil-transplant assays further showed that pathogen-induced rhizosphere soil significantly suppressed disease symptoms in XHJ, demonstrating that pathogen challenge reshapes the rhizosphere microbiota toward a resistance-enhancing configuration. Community profiling revealed that both field soil and pathogen-induced rhizosphere soil possessed higher bacterial diversity and altered abundance of multiple taxa, most prominently *Methylobacterium*. Concomitantly, tobacco plants grown in these soils displayed enhanced activation of SA-, JA-, and ET-responsive defense genes—including *NtPR1a/c*, *NtPR1b*, and *NtACS2*—with *NtPR1b* showing the strongest induction, pointing to a microbiota-enhanced immune state. Together, our findings demonstrate that pathogen infection triggers a plant-mediated recruitment of beneficial rhizosphere microorganisms, which in turn strengthens host immunity. This work provides mechanistic insight and foundational evidence for leveraging microbiome assembly to improve plant disease resistance.

# Easily biodegradable organic materials serve as soil biostimulants to rapidly enhance soil aggregate stability by increasing fungal biomass

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**ABSTRACT**

Soil microbial communities play a crucial role in the formation and stabilization of soil aggregates. The application of biostimulants that enhance the activity of native beneficial microorganisms offers a promising approach to rapidly improving soil structure in agriculture. However, this strategy remains underexplored and underutilized. In this study, we conducted a soil incubation experiment using two easily biodegradable and cost-effective carbon sources—kitchen waste hydrolysate and sugarcane molasses—as biostimulants. Our objective was to evaluate their impact on soil structure and fertility enhancement and to uncover the microbial mechanisms driving soil particle aggregation. The results demonstrated that both biostimulants: (1) rapidly increased the proportion of soil macro-aggregates and aggregate stability, while decreasing soil bulk density; (2) sustainably elevated soil dissolved organic carbon (DOC), sucrase (S-SC), and acid phosphatase (S-ACP) activities over 80 days; and (3) enhanced total soil biomass (bacteria, fungi, and protozoa) and soil biological extracellular polymeric substances (EPS) content. Both biostimulants significantly enriched putative beneficial microbial taxa that may enhance soil quality. Correlative analysis identified 16 small-molecule carbon sources (monosaccharides, disaccharides, short-chain fatty acids) in the biostimulants that facilitated soil aggregation by selectively recruiting native Gammaproteobacteria, Actinobacteria, and Microbotryomycetes. Random forest analysis revealed that DOC and fungal biomass were the primary determinants of aggregate stability. Partial least squares path modeling confirmed that biostimulants primarily improved soil structure and fertility by stimulating fungal activity. Fungi mediated the enhancement of soil aggregate stability through direct action or by producing EPS-proteins, while bacteria indirectly improved aggregate stability by producing EPS-polysaccharides. These findings provide theoretical and technical guidance for measures aimed at rapidly improving soil structure based on biostimulation methods, and hold significant implications for sustainable agricultural development.

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# Comparison of Soil Microbial Community Structure in the rhizosphere of Diploid, Triploid and Tetraploid Watermelons

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**ABSTRACT**

(1) Background: This study compared the rhizosphere microbial communities of diploid, triploid, and tetraploid watermelons. We aimed to elucidate how ploidy shapes the micro-ecological environment, adaptation, seedless and resistance. The findings are expected to provide a theoretical basis for innovating watermelon breeding strategies and harnessing beneficial plant-microbe interactions.
(2) Methods: High-throughput sequencing technology was employed to analyze the community structure of rhizosphere bacteria and fungi associated with diploid, triploid, and tetraploid watermelons.
(3) Results: The alpha diversity of rhizosphere bacterial communities was significantly higher in triploid watermelons than in the diploid and tetraploid types. Functional prediction indicated that membrane transport, carbohydrate metabolism, and amino acid metabolism were the most abundant pathways in bacterial communities across all ploidy levels, with significant functional variations observed among them. Triploid watermelons also exhibited the highest rhizosphere fungal diversity. Community composition analysis revealed distinct dominant bacterial and fungal taxa associated with each ploidy level. Integrated analysis showed that the overall bacterial community structure was most strongly influenced by triploid watermelon roots. This may be linked to their unique genetic characteristics and the resulting pronounced effect on the root micro-ecological environment.
(4) Conclusions: This study reveals that ploidy level is a key factor shaping the rhizosphere microbiome in watermelons Triploid watermelons assemble a distinct microbial community through the specific selection for and against certain taxa. These insights offer a theoretical basis for optimizing cultivation practices to enhance yield and quality.
**Keywords:** Watermelon; ploidy; rhizosphere; soil microbial communities; Micro-ecological environment

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# Comparative Analysis of Soil Microbial Community Structures in Rhizosphere of Two Texture-Differentiated Lotus Root Varieties

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**ABSTRACT**

To investigate the relationship between the rhizosphere microbial community structure and lotus root texture, the biological properties, and the rhizosphere microbial composition of mealy (ML) and crunchy lotus (CL) varieties were all analyzed using traditional and high-throughput sequencing technologies. The results showed that the ML varieties exhibited significantly lower moisture but higher starch contents than those of CL. Meanwhile, the rhizosphere fungal richness of ML was also significantly higher than that of CL. Moreover, the relative abundances of bacterial phyla and genera, such as Nitrospirota, Bacteroidota, Proteobacteria, and *Bacillus*, alongside fungal phyla and genera, i.e., Ascomycota and *Emericellopsis*, were enriched in rhizosphere of ML compared to CL. Functional prediction also revealed that elevated nitrogen cycling, polysaccharide degradation and cellulose breakdown functions could be detected in ML, potentially driving starch accumulation and cell wall modification. These results suggest that rhizosphere microbial composition, particularly nitrogen-cycling bacteria and lignocellulose-degrading fungi, may contribute to texture formation between texture-differentiated lotus root varieties.

**Keywords:** lotus root; rhizosphere; microbial compositions; polysaccharides; texture variation

**Acknowledgments**

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# Effects of Different Fertilization Regimes on Aromatic Components and Root-associated Microbiota in Peppermint (Mentha piperita L.)

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**ABSTRACT**

To explore the effects of different fertilizers on the value of peppermint essential oil and its mechanisms, apot experiment was conducted with five treatments: Organic Fertilizer (A), integrated organic-inorganic fertilizer (B), chemical fertilizer (C), no fertilization (D), and unplanted control soil (CK). The results showed that t the highest total terpenoid output (7.33 ± 0.72 mg $g^{-1}$ FW) and significantly increased menthol and isomenthol in treatment B compared to other treatments ($P$<0.05). In the root endosphere, bacterial diversity was highest under organic amendment (A) and lowest under chemical fertilizer (C). In contrast, fungal Shannon diversity was highest in C, followed by A ≈ D > B. Organic amendment enriched beneficial bacteria (e.g., Rhodococcus, Massilia) and fungi with suppressive functions (e.g., Chaetomium). Endosphere microbial networks exhibited higher diameter and clustering coefficients than rhizosphere networks, suggesting greater stability and resistance to disturbances. Integrated organic-inorganic fertilization optimized soil nutrient availability and enhanced microbiome functionality, leading to improved essential oil biosynthesis. Organic fertilization alone was most effective in maintaining endophytic bacterial diversity and beneficial functional groups. Fertilization regime had a stronger influence on endosphere than rhizosphere network stability. We recommend combined organic-inorganic fertilization as a preferred strategy for enhancing both biomass and essential oil production in peppermint.

**Keywords:** Organic–inorganic fertilization; Essential-oil terpenoids; rhizosphere microbiome; Root-endosphere microbiome; Peppermint

**Acknowledgments**

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# Differences of soil microbial community structures in rhizosphere between gynoecious and monoecious cucumbers

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**ABSTRACT**

Cucumber sex expression is a key agronomic trait determining yield, but whether its formations is related to rhizosphere soil microbes remains poorly understood. This study compared the soil microbial community structures in rhizosphere between gynoecious and monoecious cucumbers to identify potential associations. The results showed that bacterial genera including *Sphingomonas*, norank_f__*JG30-KF-CM45*, and norank_f__norank_o__*Saccharimonadales* were significantly enriched in the rhizosphere of the gynoecious cucumber. In contrast, norank_f__norank_o__norank_c__*KD4-96* and norank_f__norank_o__*Rokubacteriales* were significantly enriched in rhizosphere of the monoecious cucumbers. For fungi, genera such as *Aspergillus*, *Plectosphaerella*, and *Chaetomella* were enriched in rhizosphere of the gynoecious cucumbers. Conversely, *Trichoderma*, *Emericellopsis*, *Collariella*, and *Cordana* were significantly enriched in rhizosphere of the monoecious cucumbers. Functional prediction revealed that multiple nitrogen-cycling processes of bacterial communities, including nitrification, aerobic nitrite oxidation, nitrite ammonification, nitrate ammonification, aerobic ammonia oxidation, and arsenate respiration were detected in rhizosphere of the gynoecious cucumbers. By contrast, hydrocarbon degradation functions, particularly those for aromatic and aliphatic non-methane hydrocarbons were significantly enriched in rhizosphere of the monoecious cucumbers. Moreover, the rhizosphere of gynoecious cucumber harbored a higher abundance of saprotrophic and symbiotrophic fungi but a lower abundance of pathotrophic fungi compared to the monoecious cucumbers. These findings demonstrate that the composition and potential functions of the rhizosphere microbiome differ between gynoecious and monoecious cucumber, indicating that soil microbes in rhizosphere may play a role in the sex expression of cucumber varieties.

**Keywords:** Cucumber (*Cucumis sativus* L.); Sex expression; Rhizosphere; Soil microbial community structure

**Acknowledgments**

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# Ozonate Irrigation: Soil Microbial Stress, Nematode Suppression and Tomato Brown Rugose Fruit Virus control

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## ABSTRACT

Ozonated water ($O_3$), owing to its strong oxidizing and biocidal properties, has been proposed as a sustainable alternative to conventional plant-protection products. However, its effects on soil biological functioning and plant performance under biotic stress remain not fully understood. This study aims to evaluate the response of the soil–plant system to ozonated water irrigation, focusing on its effects on soil microbial processes, nutrient dynamics, plant growth, and its potential role in mitigating the biotic stress caused by tomato brown rugose fruit virus (*Tobamovirus frutctirugosum* - ToBRFV) and root-knot nematodes (*Meloidogyne incognita* Kofoid & White).

Greenhouse experiments were conducted using tomato (*Solanum lycopersicum* L.) under three irrigation regimes: tap water (control), ozonated water applied before transplanting (Pre $O_3$), and ozonated water applied after transplanting (Post $O_3$), in the presence or absence of ToBRFV infection. In parallel, trials on tomato (*Solanum lycopersicum* L.) and cucumber (*Cucumis sativus* L.) evaluated the effectiveness of ozonated water against *M. incognita*, comparing pre- and post-transplant applications.

Ozonated water significantly altered soil biological functioning. Both Pre $O_3$ and Post $O_3$ treatments reduced soil microbial biomass C and N, indicating a decline in soil biological fertility. The higher microbial respiration ($CO_2$) and increased metabolic quotient ($qCO_2$) suggesting oxidative stress and reduced microbial efficiency. Ozonated water also enhanced N transformations, promoting ammonification and nitrification, as reflected by higher soil $NO_3^-$ concentrations, particularly under Pre $O_3$ treatment. However, ozonated water did not mitigate the negative effects of ToBRFV infection on tomato plants; instead, pre-transplant ozone application further reduced biomass in virus-infected plants, indicating an amplification of stress under combined oxidative and viral pressure.

Conversely, ozonated water proved effective in reducing populations of *M. incognita*, especially when applied before transplanting. Pre $O_3$ treatments significantly decreased soil nematode density, root galling, and plant damage in both tomato and cucumber. This enhanced efficacy is likely due to the absence of host plants during pre-transplant application, which increases nematode exposure to ozone, impairing juvenile mobility and host root penetration.

Overall, ozonated water irrigation induced oxidative stress within the soil–plant system, negatively affecting microbial biomass and efficiency and failing to alleviate viral infection, while demonstrating promising nematicidal and nematostatic effects when applied before transplanting. These findings highlight the need for careful, context-specific application strategies to maximize the benefits of ozonated water while minimizing potential risks to soil biological health.

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# Unlocking Multifunctionality: The Interplay Between Legume-Cereal Intercropping, Soil Microbial Communities, and Ecosystem Cycles.

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**ABSTRACT**

The sustainable intensification of agriculture requires systems that optimize both yield and ecosystem services. This study, part of the Horizon Europe funded project LEGUMINOSE, evaluates the multifunctionality of intercropping systems across varying pedo-climatic conditions in Europe. We analyzed 2,309 samples comprising bulk soil, rhizosphere, and roots from seven field trials to assess the impact of intercropping on nutrient cycling, greenhouse gas emissions, and soil microbial diversity.

Methodological approaches included physico-chemical profiling combined with microbial community analysis via qPCR and Next-Generation Sequencing (NGS). A major challenge identified was the strong influence of indigenous soil heterogeneity, specifically organic carbon (OC) variability, on microbial enzyme patterns, which necessitated the use of linear mixed-effects models to isolate treatment effects.

Our results indicate that while intercropping has a limited short-term impact on the Soil Organic Carbon (SOC) cycle, it acts as a strong driver of the Nitrogen (N) cycle, significantly enhancing nutrient turnover efficiency. At the biological level, intercropping functions as a filter, causing the distinct root microbial communities of cereals and legumes to converge when grown together. Furthermore, agronomic analysis revealed a Land Equivalent Ratio (LER) of 1.16, confirming that legume-based mixtures can achieve higher productivity than monocultures while simultaneously enhancing crop resilience and nutrient use efficiency. These findings suggest that legume-cereal intercropping is a viable strategy for stabilizing yields and mitigating environmental footprints in European agriculture.

**Acknowledgments**

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# Harnessing Halophyte Microbiomes to Build Wheat Resilience under Extreme Coastal Salinity

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**ABSTRACT**

Global warming and sea-level rise are accelerating soil salinization in coastal ecosystems, threatening food security, ecosystem stability, and soil carbon sequestration. Developing nature-based solutions that sustain soil and plant health under these conditions is therefore critical.

Halophytes, naturally adapted to saline environments, rely on tightly co-evolved microbial partners that support their survival under high salt stress. Here, we explored whether wild halophyte-associated microbial communities could be leveraged to enhance wheat tolerance to saline soil. A total of 510 bacterial isolates were obtained from the rhizosphere and endosphere of coastal halophytes along the Oman Sea and Baltic Sea. Rather than selecting microbes solely based on classical plant growth-promoting traits, we used plants themselves as biological filters. Salt-tolerant, non-antagonistic isolates were assembled into microbial consortia and inoculated into six wheat cultivars, grown in saline soil.

Plant responses varied strongly among cultivars and consortia. While some treatments markedly enhanced biomass (up to 228% in *Pishgam* and 127% in *Ofoq* with Consortium 3), others caused growth suppression (33% reduction in Arg with Consortium 7). Microbial community structure analysis revealed a shared core of 122 operational taxonomic units (OTUs) across treatments; however, β-diversity (UniFrac) analyses demonstrated pronounced genotype-specific microbial filtering. The salt-tolerant cultivar *Ofoq* maintained a rhizosphere microbiome closely resembling its uninoculated control (distance = 0.285), buffering negative effects, whereas the sensitive cultivar *Bam* showed a stronger microbial shift (distance = 0.401) associated with reduced growth. These patterns highlight the decisive role of root-exudate-mediated selection in shaping functional microbiomes.

Our findings demonstrate that the success of microbial inoculation under extreme salinity depends on genotype–microbiome compatibility, not inoculum composition alone. Harnessing native halophyte-associated microbes through plant-driven selection offers a promising, low-input strategy to enhance crop resilience, stabilize coastal soils, and reduce carbon losses under climate change.

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# Recovery Mechanism of Kobresia humilis in Alpine Meadows

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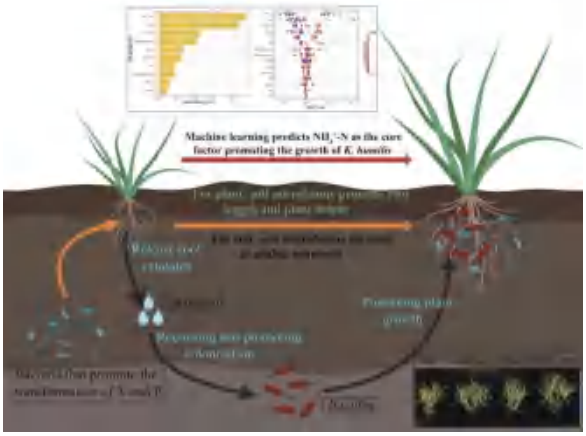
**ABSTRACT**

Alpine meadows, as crucial components of biodiversity and ecosystem services, are facing increasingly severe degradation issues, necessitating effective restoration strategies. This study investigated the recovery mechanism of *Kobresia humilis* (*K. humilis*), a group species in alpine meadows. By measuring the physiological activity, phenotype, soil nutrients, and rhizosphere microorganisms of *K. humilis* under varying degradation levels and enclosure durations, this study discovered that *K. humilis* resists grassland degradation by boosting its reactive oxygen species scavenging activity. Soil nutrients, which decline with grassland degradation, were restored after enclosure. Analysis of the rhizosphere microorganisms of *K. humilis* revealed that the microbial network in its rhizosphere becomes more complex and more unstable with grassland degradation. Microbial ecological functions, such as chemoheterotrophy, which decline with grassland degradation, were restored after enclosure.

Furthermore, across two annual samplings, a specific *Bacillus* species was consistently enriched in the rhizosphere of taller *K. humilis* plants, from which the representative strain D334 was isolated. By measuring the root exudates of *K. humilis* and correlating metabolomic and microbiomic data using Spearman correlation and the model-based integration of metabolite observations and species abundances 2 (MIMOSA2), we found that substances such as flavonoids were significantly positively correlated with *Bacillus* enrichment. In vitro experiments verified that *K. humilis* can recruit *Bacillus* by releasing baicalin and promote *Bacillus* growth by releasing riboflavin and sucrose.

To identify key drivers for *K. humilis* recovery, we integrated soil-plant data using machine learning: random forest and eXtreme Gradient Boosting models interpreted via SHapley Additive exPlanations (SHAP) analysis. Models consistently identified soil ammonium nitrogen ($NH_4^+$-N) as the primary factor promoting *K. humilis* phenotype. Ultimately, pot experiments showed that co-applying *Bacillus* and $NH_4^+$-N synergistically increased *K. humilis* plant height by 63.3%. Moreover, *Bacillus* promoted an increase in soil $NH_4^+$-N content. This provides a biological-chemical restoration method for the recovery of *K. humilis*.

**Keywords:***K. humilis*, microbiome, *Bacillus*



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# Establishing Genetic, Phylogenetic and Functional Mechanisms that Shape Acidobacteriota Diversity of Arctic Tundra and Boreal Forest Soils

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**ABSTRACT**

Increasing temperatures in Arctic tundra and boreal forest ecosystems are leading to higher microbial respiration rates of soil organic matter, resulting in the release of carbon dioxide and methane. To understand the effects of this microbial activity, it is important to better characterize the diverse microbial communities in these soil habitats. The *Acidobacteriota* are ubiquitous and abundant in tundra and boreal forest soils, however the genetic taxonomic and functional diversity within this bacterial phylum remain poorly known. Our aim is to refine the phylogenetic and functional diversity of the ubiquitous, but elusive, members of the *Acidobacteriota* phylum so we can link their diversity to different soil habitats and elucidate the mechanisms which shape their communities in soils. Bacteria excel at adapting to different environments, but the functional implications of community transitions need to be characterized. The overarching hypothesis is that resource partitioning, selective predation, and temporal separation of activity each contribute to the success of a particular bacterial strain/species. Laboratory- and field-based approaches are used to discern which species are successful and explain why, with a focus on sub-Arctic tundra and boreal forest soil habitats. From a set of long-term tundra and forest field sites we are collecting data on how the soil *Acidobacteriota* communities are selected across environmental gradients. The long-read capability of the Oxford Nanopore MinION is used to profile bacterial ribosomal RNA operons of soil communities and isolates in order to build a comprehensive rRNA operon sequence database of the *Acidobacteriota* with strain-level resolution. Assembled full *Acidobacteriota* genomes, multi-locus phylogenies, and annotated pangenome markers are utilized to differentiate *Acidobacteriota* species. By uncovering novel species and strains within the *Acidobacteriota* and improving the accuracy of their phylogenetic placements, we aim to enhance our understanding of this complex phylum and elucidate the mechanisms which shape microbial communities in soils.

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# Impact of multiple driving factors on soil bacterial community dynamics in a wheat-maize/soybean rotation system in the North China

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## ABSTRACT

Sustainable management of crop rotation systems is critical for maintaining soil fertility, microbial diversity, and crop productivity in intensive agroecosystems. The Huang-Huai-Hai region, a major grain-producing area in China, predominantly employs a wheat-maize double-cropping system, often causing nutrient imbalances and soil degradation. Introducing legume rotations may improve soil quality and microbial functioning. Here, we investigated the effects of summer crop type (soybean vs. maize), location, ecological compartment (bulk vs. rhizosphere soil), and management practices (fertilization and straw returning) on soil bacterial communities using cross-regional field platforms established in 2017. Soil physicochemical properties, bacterial diversity, community composition, co-occurrence networks, and assembly mechanisms were analyzed.

Geographical location was the strongest environmental filter, explaining up to 34.15% of community variation, exceeding effects of ecological compartment and management. Crop type modulated responses to management: bacterial communities in maize were more sensitive to fertilization than in soybean. Community composition showed clear geographic differentiation: SZ and WS were enriched in *Sphingomonas* and *Lysobacter*, while YC was enriched in *Burkholderia*. CCA identified key drivers: clay content, soil water, and pH drove SZ/WS differentiation; sand content and $NH_4^+$-N drove XX/YC variation.

Network analysis revealed functional topological differences: soybean supported more complex (nodes/edges) and stable (higher clustering coefficient) networks; maize exhibited higher modularity and positive interaction proportion. Key ecological modules, enriched in nitrogen-cycling taxa (*Nitrospira*, *Nitrosospira*), were strongly influenced by management. Neutral model analysis indicated stochastic processes dominated community assembly (maize > soybean; bulk > rhizosphere), but rhizosphere conditions and fertilization increased deterministic selection.

Overall, regional soil background sets the foundational framework for bacterial community patterns, while crop type, via rhizosphere processes and interactions with management, regulates network stability and community assembly. Incorporating soybean into cereal rotations can enhance microbial network robustness and optimize community assembly, providing mechanistic insights for microbiome-informed sustainable intensification in agriculture.

# Microbial Hydrogen Cycling as a Potential Driver of Drought Resistance in Agricultural Soils

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## ABSTRACT

Studies in natural and dryland ecosystems demonstrate that hydrogen-oxidizing microbes can survive prolonged drought by utilizing atmospheric $H_2$ to meet basal energetic demands. However, how hydrogen cycling operates in agricultural soils and whether these mechanisms are relevant for agroecosystems remain poorly characterized.

Here, we investigated soil $H_2$ cycling in a soybean agroecosystem which represent a well-established biological source of $H_2$ in soils. We quantified soil $H_2$ production and measured depth-resolved $H_2$ oxidation rates under field conditions, revealing pronounced vertical structuring of hydrogen oxidation within the agricultural soil profile. Notably, $H_2$ oxidation rates were consistently higher in upper soil layers, which are typically subject to greater environmental variability and resource limitation.

We further identified a significant positive linear relationship between soil moisture and $H_2$ oxidation rates within a moisture range (0.10–0.25 gravimetric water content), which is consistent with previous studies. This pattern indicates that soil moisture modulates $H_2$ oxidation capacity but does not solely determine it. Comparisons between agricultural and adjacent forest soils revealed distinct land-use–specific $H_2$ oxidation rates and differences in the abundance of high-affinity hydrogenase genes (*hhyL*).

Together, these findings suggest that biologically mediated $H_2$ inputs and depth-structured hydrogen oxidation contribute to microbial persistence and community stability in agricultural soils, consistent with survival mechanisms previously described in drought-prone ecosystems. We propose that $H_2$ cycling represents an underappreciated process linking microbial survival strategies to soil resilience in agriculture. Ongoing work will explore how $H_2$-driven microbial persistence interacts with crop systems, particularly leguminous crops such as soybean, to assess its potential role in agricultural drought resilience.

**Keywords:** Microbial persistence, Water-limited soils, Trace gas metabolism, Legume agroecosystem, Soil biogeochemistry

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# Fungal mutualism in plant growth: dark septate endophytes and arbuscular mycorrhizal colonization in soybean (Glycine max)

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**ABSTRACT**

Endophytes are host-associated microbial communities that colonize intercellular and/or intracellular spaces, while arbuscular mycorrhizal fungi (AMF) are root-associated symbiotic fungi that form mutualistic relationships with plants. Both groups enhance plant performance through nutrient acquisition, stress tolerance, and growth promotion, while benefiting from plant-derived carbon. In this study, we investigated the dual partite interaction between AMF colonization and dark septate fungal endophytes (DSE: Thozetella neonivea, Leptodontidium orchidicola) on the growth and yield of soybean (Glycine max) grown in the field.

The DSEs were applied to seeds at three different dosages (low, medium, and high). All seeds were counter-coated with rhizobium bacteria, while the control treatment only had the rhizobium. We quantified AMF colonization based on the presence of arbuscules and documented the presence of other fungal structures (e.g., vesicles, fungal coils) using microscopy. AMF colonization levels were significantly higher in the DSE-inoculated treatments compared to the controls. This enhancement in AMF colonization correlated with increased plant growth (total dry biomass, root mass) and grain yield, with the medium DSE dosage producing the most pronounced effects compared to the control. However, a decline in plant performance was observed at the high dosage, suggesting a possible microbial imbalance.

Our results indicate that the inoculation of soybean seeds with the DSEs improved the naturally occurring AMF and plant growth, irrespective of the endophyte strain. This suggests a synergistic interaction between DSEs and AMF in the soybean rhizosphere. However, excessive DSE application may disrupt this balance, potentially altering the microbial network and negatively affecting AMF symbiosis and plant growth. DSE dosage is a critical factor influencing this dual symbiotic relationship. We conclude that targeted DSE inoculation can enhance AMF colonization, plant biomass, and yield in soybean, offering a promising strategy for sustainable crop improvement.

# Synergistic Soil Remediation and Microbial Network Reconstruction: Leguminous Cover Crops and Probiotics in Degraded Dry-Hot Valley Coffee Plantations

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## ABSTRACT

Soil degradation poses a critical threat to agroecosystem sustainability in ecologically fragile dry-hot valleys, where intensive coffee cultivation has exacerbated soil erosion, nutrient depletion, and microenvironmental deterioration.As a promising eco-friendly remediation strategy, the combined application of leguminous cover crops and probiotics has shown great potential in reversing soil degradation, yet the underlying synergistic mechanisms governing soil physicochemical improvement and microbial community restructuring remain poorly elucidated, limiting its large-scale deployment.

To address this knowledge gap, a one-year field experiment was conducted in a degraded coffee plantation in the Jinsha River dry-hot valley, with three treatments established: monoculture of *Medicago sativa L.* inoculated with *Bacillus cereus* strain 4-8 (ZB1), mixed culture of *Medicago sativa L.* and *Vicia villosa var. glabrescens* inoculated with the same strain (ZB2), and a fallow control (ZCK).Comprehensive analyses were performed to assess the impacts of different treatments on soil chemical properties, key enzyme activities, bacterial community composition, and species co-occurrence networks.

The results demonstrated that the combined legume-probiotic treatments exerted a pronounced synergistic effect on soil remediation and reclamation: ZB1 treatment effectively optimized soil pH from weakly alkaline to neutral, while significantly increasing total nitrogen and potassium contents; both ZB1 and ZB2 treatments markedly elevated nitrate nitrogen levels, thereby enhancing nitrogen sequestration and mitigating nutrient leaching risks. Concurrently, the activities of soil enzymes involved in carbon, nitrogen, and phosphorus cycling were significantly upregulated, indicating the activation of microbial metabolic functions critical for soil nutrient transformation. At the microbial community level, the combined treatments drove a distinct shift in dominant bacterial phyla from Acidobacteria to Bacteroidetes, with a notable enrichment of beneficial taxa including *Xanthomonas* and *Rhodobacterium.* Redundancy analysis further identified total nitrogen as the pivotal edaphic factor driving bacterial community assembly, establishing a direct causal link between soil physicochemical remediation and microbial community restructuring.

This study provides the first field-scale empirical evidence for the cascading synergistic pathway underlying legume-probiotic mediated soil improvement, and proposes a practical, scalable remediation strategy for degraded dry-hot valley agroecosystems. The findings offer robust scientific support for advancing global efforts in soil degradation control and sustainable soil management, contributing to the realization of the "a shared future for soil and humanity" initiative.

**Acknowledgments**

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# Integrated impacts of land use intensification on greenhouse gas emissions and soil microbial communities in the Taihu Lake Region: patterns, mechanisms, and implications

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**ABSTRACT**

The Taihu Lake region has experienced rapid land use intensification, characterized by conversions from natural wetlands (NW) to conventional rice-wheat rotation fields (RW) and further to greenhouse vegetable fields (GH), driven by economic interests. While such transformations are widespread, their combined effects on greenhouse gas (GHG) emissions and underlying soil microbial mechanisms remain poorly understood. This integrated study addresses these gaps through multi-faceted analyses of GHG fluxes, soil microbial communities, and nitrogen (N)-cycling functional genes across NW, RW, and GH sites. Two-year in-situ field experiments revealed significant GHG emission shifts: land use intensification reduced methane ($CH_4$) emissions (NW: 970.66 ± 100.09 kg C $ha^{-1}$; RW: 896.71 ± 300.44 kg C $ha^{-1}$; GH: 71.23 ± 63.62 kg C $ha^{-1}$) but markedly increased nitrous oxide ($N_2O$) emissions (NW: 3.35 ± 0.44 kg N $ha^{-1}$; RW: 14.38 ± 4.09 kg N $ha^{-1}$; GH: 81.62 ± 4.89 kg N $ha^{-1}$). Global warming potential followed the order RW > NW > GH, indicating intensified comprehensive greenhouse effects during NW→RW conversion and mitigation during RW→GH conversion. Microbial community analyses showed land use intensification directly altered bacterial and fungal compositions, with stronger impacts on bacteria. Bacterial communities correlated closely with soil $NO_3^-$-N, pH, and electrical conductivity, exhibiting decreased deterministic processes (opposite to fungi). Arable lands (RW/GH) displayed more complex microbial networks, and seasonal variations (notably summer) influenced microbial diversity and function, though less strongly than land use effects. Integrating quantitative PCR and metagenomics uncovered microbial mechanisms driving $N_2O$ emissions: intensification reshaped N-cycling microbial communities, depleting nitrogen fixation, dissimilatory nitrate reduction to ammonium, and anammox marker genes in GH soils. Denitrifying communities segregated similarly to total N-cycling assemblages, with increased network complexity but divergent stability. Critically, intensification amplified $N_2O$ emission potential by elevating Pseudomonadota harboring *nirK*/*norB* genes (and associated communities) while reducing *nosZ* (encoding $N_2O$ reductase) abundance—directly linking microbial functional imbalance to emission increases. Collectively, this study demonstrates that land use intensification in the Taihu Lake region drives GHG emission trade-offs (reduced $CH_4$ but amplified $N_2O$) and restructures soil microbial communities and N-cycling functions. These findings highlight the need to prioritize microbial functional balance (e.g., restoring *nosZ*-carrying taxa) in mitigation strategies, providing critical insights for sustainable land management in wetland-agricultural transition zones.

**Acknowledgment**

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# Soil microbial communities regulate plant response to drought stress

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**ABSTRACT**

Soil biodiversity, essential for ecosystem functioning and plant resilience, is increasingly threatened by climate change and agricultural practices. While the impact of soil biodiversity loss on plants like legumes and grasses has been demonstrated, its effect on potatoes remains underexplored. This study addresses this gap by investigating how different microbial diversity gradients, including the presence of phages, influence potato growth and resilience under drought stress in a controlled climate chamber experiment. Our findings reveal that varying microbial diversity leads to distinct plant growth patterns, with low-diversity treatments suppressing plant recovery post-stress. Higher abundance of phages enhanced plant performance during drought stress, although no significant effect on recovery was observed. Notably, we demonstrate that soil microbial diversity significantly alters root exudate profiles, suggesting that interactions between root metabolites and the microbiome may regulate plant growth and responses to environmental disturbances. Furthermore, correlation analysis revealed a positive correlation between soil microbial diversity and plant productivity, particularly during the recovery period following drought stress, emphasising the critical role of the soil microbiome in supporting plant resilience. These findings underscore the importance of maintaining healthy soil microbial communities to enhance plant drought tolerance and sustain agricultural productivity in the face of climate change.

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# Assessing the Role of Soil Amendments and Root-Associated Fungi in Anaerobic Soil Disinfestation

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**ABSTRACT**

Anaerobic soil disinfestation (ASD) is a promising alternative to soil fumigation for suppression of strawberry black root rot complex pathogens, including pathogens in the *Fusarium oxysporum (Fo)* species complex. Soil treatment by ASD is facilitated by in-situ fermentation of organic soil amendments, which induces production of pathogen-suppressing reduced iron and manganese cations and volatile fatty acids (VFAs). However, little is known about how amendment composition influences *Fo* suppression and crop health via root-associated fungal communities in ASD. The influence of amendment composition on *Fo* suppression, crop health, and root-associated fungi was studied in strawberry pot trials in a greenhouse pot trial, using dried molasses, wheat bran, spent brewer's yeast, and Azolla meal amendments. Soil solution VFA and reduced metal concentrations, soil pH, and Fo inoculum viability were measured post-ASD. Plant biomass (as a proxy for crop health) was measured and roots sampled to determine endophytic colonization rates of beneficial mycorrhizae/endophytes by ITS2 amplicon sequencing. The influence of amendment type on VFA and reduced metal concentrations and *Fo* suppression was minimal due to low VFA and reduced metal concentrations owing to limited anaerobic conditions. However, some ASD amendments (i.e, molasses and wheat bran) were associated with enhanced plant health or abundance of key root-associated fungi (e.g., dried molasses and Serendipitaceae). Higher abundance of Trichoderma spp., members of the order Agaricales, and members of the family Serendipitaceae was positively associated with root and/or shoot biomass. Our results highlight the importance of ASD amendment properties and root-associated fungi in influencing crop health when ASD treatments do not provide adequate treatment effects through decomposition byproducts such as VFAs and reduced metals.

# Fungal community shifts govern microbial carbon use efficiency across an elevation gradient at Qinling mountain, China

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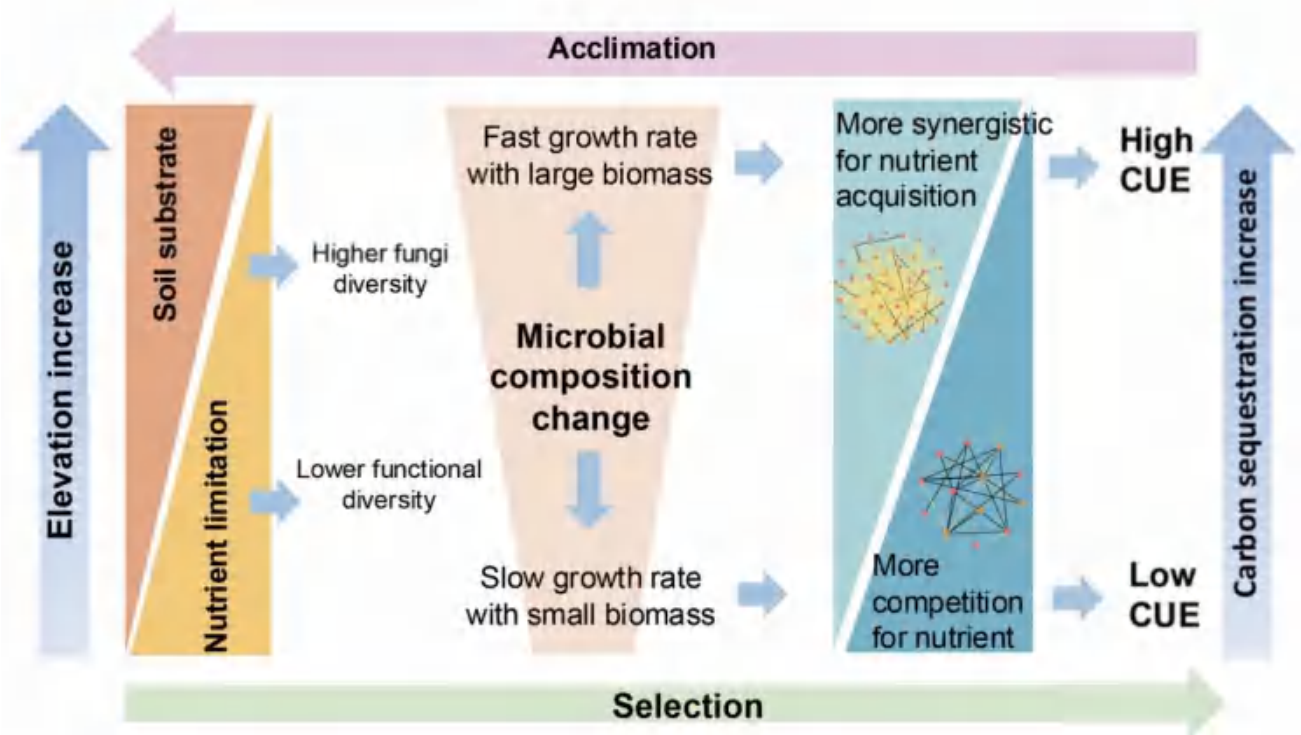
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**ABSTRACT**

Microbial carbon use efficiency (CUE) is a critical factor affecting soil organic carbon (SOC) dynamics. However, the relative importance of biotic and abiotic drivers of CUE variations remains debated, resulting in large uncertainties in SOC predictions. In this study, we combined field sampling with isotope labeling experiments to identify the driving factors of changes in microbial CUE along an elevation gradient (1,200–2, 400 m) of Qinling mountain. Our results demonstrated that higher elevations (2,000–2,400 m) resulted in greater microbial CUE, which partially aligned with the enhancement of SOC sequestration and the total SOC content change. The fungi-dominated cluster served as the directed CUE dynamics, while soil nutrients acted as the indirect factor affecting CUE by regulating the structure and interactions of the microbial community. Notably, the dominance of fungal taxa at higher elevations, shaped by substrate properties, promoted faster growth and stronger synergistic interactions within the microbial network, leading to higher CUE. These findings highlight the importance of integrating the taxonomic and functional traits of microbial communities to predict community-level CUE and SOC dynamics under global change.

**Graphical ABSTRACT**



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# Microbial Drivers of High Fertility in Black Soil: A Metagenomic Perspective on Enhanced Nutrient Cycling and Metabolic Resilience

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## ABSTRACT

The black soil region of Northeast China, often termed the “giant panda of farmland” in China, is vital for national food security and agricultural sustainability. Intensive cultivation, however, has accelerated soil degradation, underscoring the urgent need to understand the microbial mechanisms that sustain its fertility. While black soil is known for high organic matter and nutrient content, the structural and functional links between its microbial communities and soil productivity remain unclear. Here, we conducted comparative metagenomic analyses of black soil alongside other major agricultural soils—fluvo- aquic, red, and saline- alkali soils—to systematically characterize the microbial features underpinning black soil fertility.

In the dryland black soil sampled from Lishu County in this study, Actinomycetota dominated at the phylum level, representing >64% of annotated genes. At the family level, marked enrichments were observed for Nocardioidaceae, Pseudonocardiaceae, Paraconexibacteraceae, and Sphingomonadaceae. The exceptional abundance of Nocardioidaceae (>18%) suggests a key role in decomposing complex organic matter. Functionally, KEGG annotation revealed elevated gene abundances linked to amino acid metabolism, carbohydrate metabolism, and energy metabolism, reflecting heightened organic matter transformation and energy flux. Black soil also showed superior gene representation in cofactor and vitamin metabolism, transport and catabolism, xenobiotics biodegradation, and lipid metabolism. Complementary eggNOG analysis further confirmed enhanced functional potential in carbon transport and metabolism, transcription, cell cycle control, cell division, lipid metabolism, secondary metabolite biosynthesis and transport, and iron ion transport/metabolism. Absolute quantification via SmartChip- based high- throughput qPCR validated these patterns, demonstrating substantially higher abundances of key functional genes involved in carbon (e.g., fumarate reductase), nitrogen (e.g., nitrogenase iron protein, nitrite reductase), and phosphorus (e.g., pyrroloquinoline- quinone synthase, alkaline phosphatase) cycling. Annotations against the Virulence Factor Database additionally revealed significantly higher abundances of genes related to exoenzymes, immune modulation, nutritional/metabolic factors, and stress survival in black soil. This suggests that the high- organic- matter, microbially active black- soil ecosystem selects for taxa with enhanced environmental adaptability and competitive traits.

Collectively, our findings identify distinct microbial taxa and functional gene repertoires that contribute to vigorous nutrient cycling and metabolic resilience in black soil. These insights provide a genomic foundation for developing microbial- based strategies to sustain and enhance the productivity and ecological health of this vital agricultural resource.

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# Effect of biological nitrification inhibition on the rhizosphere microbiome of maize

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## ABSTRACT

Nitrification inhibitors can alleviate nitrogen loss by inhibiting nitrification. Research on biological nitrification inhibition (BNI), as an organic and environmentally friendly alternative, is gradually gaining a lot of attention for improving nitrogen use efficiency (NUE) and decreasing environmental pollution. Therefore, a deeper understanding of how biological inhibitors modulate soil nitrifiers and denitrifiers needs to be explored. A naturally nitrification-inhibiting plant, such as *Plantago lanceolata*, is an excellent model for assessing the inhibitory mechanisms of BNI. Six genotypes of *P. lanceolata* were planted as an intercropping species with maize in two different locations characterized by contrasting soil types. At BBCH 65 and 85 maize rhizosphere soil samples were collected for analysis of the activity of extracellular enzymes of the carbon (C), nitrogen (N) and phosphorus (P) cycle, to ensure that the suppression of nitrifiers by *P. lanceolata* exudates does not inhibit key functions of organic matter mineralization in soil. While ß-glucosidase (BG) and cellulase activity (CE) assess general hydrolytic microbial activities, leucine aminopeptidase (LAP) and acid phosphatase activity (AP) display nutrient-mineralizing activities. In addition, DNA and RNA were extracted and subjected to 16S rRNA gene sequencing to assess the effects of *P. lanceolata*–mediated BNI on the community composition and diversity of key nitrifiers and denitrifiers. Based on 16S rRNA gene sequencing and Tax4Fun analysis, we predicted functional genes involved in (de-)nitrification and assessed potential losses or gains of functional genes related to nitrification and denitrification. Subsequently, we went for qPCR of amoA to directly determine gene copy numbers depending on the Plantago genotypes.

We could demonstrate that P. lanceolate did not affect mineralizing enzyme activities in the maize rhizosphere and thus will not reduce mineral nutrient provision even under organic farming, where this is the kinetically limiting step controlling nutrient availability. Soil-specific effects on the microbiome exceed those of the P. lanceolate intercropping, diminishing genotype-specific effect on denitrifying and nitrifying communities across sites. This study provides molecular insights into the inhibitory processes in the rhizosphere that modulate the effectiveness of BNI. These findings pave the ground for sustainable strategies for a sustainable N-cycle management by intercropping.

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# Sustainable Alternatives to Peat-Based Growing Media: Microbial Functionality as a Key Indicator

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**ABSTRACT**

The progressive restriction of peat extraction across Europe has intensified the need to identify sustainable alternatives for horticultural growing media that maintain biological functionality while reducing environmental impact. Peat has long been valued for its favorable physical properties; however, its non-renewable nature and role in carbon storage necessitate the development of peat-reduced or peat-free substrates. This study evaluates a range of alternative growing media and their mixtures with particular emphasis on microbial metabolic activity, functional diversity, and their role in soil carbon cycling.

Microbial community-level physiological profiling was conducted using Biolog™ EcoPlates to assess respiration activity, biomass production, and functional biodiversity in several growing media, including acidic peat, peat substrates, perlite, organic topsoil-based substrates, commercial biostimulants, and mixed formulations. Analyses were performed before plant cultivation to characterize the intrinsic biological potential of the substrates.

Functional indices such as Average Well Color Development (AWCD), Average Well Density Development (AWDD), and the effective number of substrates utilized (ENbs) were used to quantify microbial metabolic intensity and diversity.

Across all tested growing media, microbial metabolism was predominantly driven by nitrogen-containing carbon sources, particularly amines and amides, followed by amino acids and carbohydrates. This pattern indicates that nitrogen-rich substrates play a key role in supporting microbial activity and growth. Mixed substrates combining mineral components with organic matter exhibited high respiration rates, strong biomass production, and broad functional diversity, often comparable to conventional peat-based substrates. In contrast, perlite alone showed very low microbial activity and minimal biomass production, confirming its biologically inert character.

Functional biodiversity analyses demonstrated that substrates enriched with organic components and biostimulants supported metabolically versatile microbial communities capable of utilizing a broad spectrum of carbon sources. Polymer utilization remained consistently low across all substrates. Notably, the balance between respiration and biomass production indicated that certain peat-reduced mixtures effectively supported carbon transformation without inducing excessive microbial stress.

Overall, the results demonstrate that well-designed peat-reduced and peat-free growing media can sustain high microbial functionality. Microbial metabolic profiling is a valuable tool for evaluating peat substitutes and optimizing substrate composition, supporting the development of sustainable horticultural systems.

**Acknowledgments**

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# Effects of inter-row management and cover crops on vineyard rhizosphere microbial communities

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## ABSTRACT

The microbial communities in vineyard rhizospheres have been the subject of considerable research, yet it remains unclear how floor management practices and cover crops affect their composition. Rhizosphere samples were collected from a long-term experimental vineyard designed to evaluate soil covering methods in erosion-prone areas (Figure). Our objective was to assess fungal diversity in vineyards differing only in floor management practices. To this end, we sampled two soil depths (10–30 cm (Shallow) and 30–50 cm (Deep)) in each vineyard. DNA was extracted using the Quick-DNA Fecal/Soil Microbe Kit following the manufacturer's instructions. Whole metagenome libraries were prepared and sequenced according to the Illumina protocol, with sequences analyzed using MEGAN6 and Kraken2 software.

Our results from this comparative long-term experiment on cover crops and tillage in an erosion-affected vineyard confirm previous literature findings: natural grass (dominated by *Lolium perenne* L.) acts as a significant water competitor for grapevines when used as cover crops. In summary, the Cover and Wheat treatments provided the best soil moisture retention, yielding the highest soil moisture values and grape water uptake. Next-generation metagenomic analyses revealed pathogenic strains comprising over 20% of the communities in three treatments Phacelia (Shallow), Wheat (Shallow), and Triticale (Shallow), whereas extremely low levels (<5%) were observed in Phacelia (Deep) and Cover (Deep). These findings can guide farmers in assessing risks associated with root disturbance (e.g., mechanical tillage in root zones), which may expose grapevines to soil-borne pathogenic fungi. The most pronounced soil disturbance occurred in the Wheat and Triticale treatments, resulting in higher pathogen ratios that warrant caution. Future evaluations of farming practices should incorporate this parameter when seeking sustainable alternatives.



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# What fungi can we count on in the mitigation of climate change influence on forests in different climatic regions – comparison of arbuscular and ectomycorrhizal solutions in Serbia and China

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**ABSTRACT**

In nature, conditions for tree growth are often harsh, and competition for nutrients and water in the soil is intense. To survive threatening conditions, plants form symbiotic relationships with different groups of fungi: arbuscular (AM) or ectomycorrhizal (ECM) symbiosis. The type of symbiosis that develops and which plants endure unfavorable conditions depend on limiting factors such as water and nutrients in their environment. In the Mediterranean, temperate, and boreal forests, trees establish both AM and ECM relationships, while in tropical regions, forests can be entirely dominated by AM. Within the eco2adapt joint project between the EU and China, we aim to determine how the mycorrhizal potential of forest plants and belowground diversity influence forest resilience to climate change. Since a plant's ability to survive largely depends on forming mycorrhizae with fungi that support them during drought or nutrient-limited conditions, we study root-associated mycobiome (RAM) communities across selected forests in Europe and China. Our focus is on linking the diversity and abundance of RAM to soil parameters, especially soil water and nutrient availability. To maximize ecological niche differences, in this contribution, we compare mixed alluvial forests in Serbia (co-dominated by ECM and AM hosts) with subtropical Moso bamboo (*Phyllostachys edulis*) forests in China (exclusively dominated by AM). Preliminary results from Chinese bamboo forests show that drought stress acts as a strong environmental filter, significantly reducing AM fungal diversity while promoting drought-tolerant genera such as *Glomus sp.* Despite a decrease in fungal diversity, the symbiotic infection rate in mature bamboo roots remains relatively stable, indicating a "core mycobiome" strategy that sustains water and nutrient uptake under stress. Preliminary findings from Serbian forests reveal marked seasonality in RAM diversity and structure, characterized by ECM dominance and the existence of a stable "core mycobiome". We aim to parameterize the soil environment that will favor specific plant/fungal communities (e.g., ECM versus AM trade-offs under water deficit) and thus enable monitoring of forest soil health, alongside the selection of forest management practices that will support forest survival in the future.

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# Soil Bacterial Succession as a Driver of Rhizosphere Function: Wheat-Derived Plant Growth-Promoting Rhizobacteria and Plant Stress Resilience

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## ABSTRACT

Rhizospheric microorganisms constitute a central component of soil biodiversity and play a pivotal role in regulating plant performance and ecosystem functioning. Among them, plant growth–promoting rhizobacteria (PGPR) represent a key functional guild, capable of modulating plant physiology, nutrient acquisition, and stress responses. Their contribution is particularly relevant in the context of climate change, where increasing frequency of drought and soil degradation threatens crop productivity and soil health. Despite their proven potential, the effectiveness of PGPR in agroecosystems remains highly variable, largely due to the complex and dynamic nature of microbial interactions within the rhizosphere and their sensitivity to environmental and management-driven perturbations. Soil moisture regimes, plant developmental stage, and community-level microbial diversity profoundly influence the establishment, persistence, and functional expression of introduced strains. Consequently, understanding how environmental constraints and agronomic practices reshape rhizosphere microbiomes is essential for translating microbial inoculants into reliable tools for sustainable agriculture.

In this study, we tested whether the phenological timing of microbial isolation influences the functional outcomes of PGPR application. Three bacterial consortia were assembled from strains isolated at distinct phenological stages of spring wheat (*Triticum aestivum* L.), tillering , elongation and ripening stage, at Brackenhurst Farm (Nottingham, UK). All isolates were previously screened in vitro for key PGPR traits, including solubilization of phosphorus, potassium, and zinc, production of indole-3-acetic acid (IAA), ammonia, and siderophores. These consortia, representing temporally structured rhizosphere communities, were inoculated onto lettuce (*Lactuca sativa* L.) seedlings grown under well-watered and drought conditions. Plant performance was assessed through tissue traits (water content and dry matter), chlorophyll content (SPAD), and gas exchange (LI-COR) after 60 days from inoculation, while lettuce growth dynamics were monitored every 10 days using high-throughput phenotyping (PlantEye).

Under well-watered conditions, none of the consortia significantly altered dry matter, water content, or canopy architecture relative to the control, indicating that PGPR effects are muted when plants operate near their physiological optimum. In contrast, drought revealed strong strain-dependent physiological modulation.

Consortia assembled from rhizobacteria isolated during the elongation and ripening stages of wheat development significantly increased leaf chlorophyll content and reduced both transpiration and intercellular $CO_2$ concentration, while maintaining net photosynthetic rates. This coordinated response reflects a more efficient regulation of stomatal aperture, enabling plants to conserve water without compromising carbon assimilation, and thus represents a clear enhancement of intrinsic water-use efficiency under drought.These effects mirror mechanisms widely reported in PGPR literature, including ACC deaminase activity, hormonal modulation, and improved nutrient acquisition. Notably, whole-plant architectural traits derived from Phenospex scanning were not significantly altered by inoculation under drought, despite clear physiological benefits at the leaf level. This scale-dependent response suggests that PGPR primarily act as stress buffers, preserving photosynthetic function and delaying functional decline rather than driving rapid biomass accumulation.

Collectively, our results demonstrate that the temporal origin of rhizosphere bacteria encodes functional specialization relevant to plant stress adaptation, linking microbial succession in soil to ecosystem-level outcomes. PGPR isolated at different phenological stages of the host plant elicit distinct physiological strategies, underscoring the ecological significance of microbial turnover and niche differentiation within the soil microbiome. These findings align with emerging concepts in soil biodiversity and soil health, emphasizing that microbial function is shaped by dynamic community assembly rather than by isolated traits. Reframing inoculants as components of evolving soil microbiomes, whose adaptive history governs their functional expression, provides a new perspective for harnessing soil microbial diversity in climate-resilient agroecosystems. This temporal dimension of soil biodiversity offers a pathway for designing microbiome-based interventions that enhance plant resilience while maintaining the integrity and functional complexity of soil ecosystems.

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# Contrasting patterns of belowground biodiversity homogenization across urban greenspaces

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## ABSTRACT

Urban greenspaces play a central role in safeguarding biodiversity and maintaining resilient cities, yet their influence on soil biotic homogenization remains unclear. We analyzed four contrasting greenspace types across major soil biota groups in 55 cities spanning a broad climatic gradient. Urban farms exhibited the highest soil biotic homogenization and pathogen prevalence. In contrast, golf courses and other structurally heterogeneous greenspaces showed low homogenization, with patterns comparable to natural ecosystems. Our results suggest that lower soil pH, higher tree cover, greater litter availability, and wetter environments may help reduce soil homogenization, and reveal that structural heterogeneity, rather than management intensity alone, determines urban soil biodiversity patterns.

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# Life and death of ammonia oxidizers drives soil organic carbon accumulation in long-term different fertilization soils

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## ABSTRACT

Agricultural soils rely on external nitrogen (N) fertilization to sustain crop productivity, which continuously activates ammonia-oxidizing microorganisms (AOMs). Although AOMs grow primarily via chemoautotrophic $CO_2$ fixation, their decay contributes to soil organic carbon (SOC) that can be respired as $CO_2$, leaving their net impact on soil carbon accumulation and neutrality unclear. This study employed two-phase microcosm incubation to examine how AOM cell proliferation and death affect SOC accumulation in long-term different fertilization black soils. During the 28-day incubation with $^{13}CO_2$ and urea (Phase I), net production of soil organic $^{13}C$ ($^{13}C$-SOC) showed no significant differences among treatments: unfertilized CK (continuous maize, 23.6 μg $g^{-1}$), chemically fertilized CC (continuous maize, 20.9 μg $g^{-1}$), CS (continuous soybean, 22.8 μg $g^{-1}$), and RCS (rotation maize-soybean, 25.0 μg $g^{-1}$). This $^{13}C$-SOC originated entirely from active ammonia-oxidizing bacteria (AOB) and archaea (AOA), with fertilized treatments showing significantly higher AOB: AOA protein-C ratios (CC: 4.48; CS: 5.88; RCS: 12.5) than CK (1.56). The mortality of active cells was further assessed (Phase II) by measuring AOM-related $^{13}C$-$CO_2$ mineralization, which was approximately twice as high in the CK compared with the fertilized treatments ($p < 0.05$) within 30 days. Moreover, we conducted a microcosm experiment using $^{13}C$-$CO_2$ and ammonium sulfate in a brown soil subjected to six long-term fertilization regimes (CK, N2, N4, M2, N2M2, N2P2). Single fertilizers (N2, N4, M2) showed the highest $CO_2$ fixation rates via ammonia oxidation (mean 13.1 μg $^{13}C$ $g^{-1}$), whereas manure treatments (M2, N2M2) emitted more $N_2O$ than inorganic fertilizers alone. The offset potential (warming equivalents of fixed $CO_2$ vs. $N_2O$) exceeded 70% in all treatments and topped 100% in N2 and N4. Notably, where AOA and AOB co-dominated (N2, N2M2), AOA-derived carbon contributed >97% of the newly fixed $^{13}C$-SOC. Long-term combined organic-inorganic fertilization (N2M2) shifted the active AOM community from AOB dominance (M2 alone) to AOA-AOB co-domination. We conclude that long-term urea application increases the AOB:AOA protein-C ratio and promotes ammonia oxidizer-derived SOC accumulation through their life cycles, ultimately supporting carbon neutrality. In contrast, ammonium sulfate application enhances the trade-off between $CO_2$ fixation and $N_2O$ emission, modulating the net greenhouse gas balance of AOM. These findings highlight the potential of optimized nitrogen fertilization to enhance carbon offset against $N_2O$ emissions in agricultural soils.

**Key words:** Ammonia oxidizing bacteria, Ammonia oxidizing archaea, soil organic carbon, $N_2O$ mitigation, DNA-SIP

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# Does land use conversion from temperate steppe to farmland increase broad scale homogeneity of soil biota and its functional genes?

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**ABSTRACT**

It is widely considered that conversion of natural landscapes to agriculture results in biotic homogenization. A recent study comparing soil biota of 27 paired natural steppe soil (NS) and agricultural soil (AS) sites across 900km in north-eastern China found that conversion to agriculture had increased spatial gradients in soil functional genes. Using the same shotgun metagenome samples, and bacterial amplicon data, we instead analyzed total observed variation at the between-site and within-site level. We found that land-use conversion from steppe to farmland diversified functional gene profiles both locally and spatially; it increased the abundances of functional genes related to labile carbon, but decreased those related to recalcitrant substrate mobilization (e.g., lignin), P cycling, and S cycling. Alpha-diversity of core functional genes was strongly related to multi-nutrient cycling in AS, suggesting a key relationship to soil fertility. From the perspective of community taxonomic composition, archaeal and fungal community variation was decreased in AS compared to NS at both within- and between-site scales. In contrast, the bacterial and metazoal community was homogenized only at the local scale. Total functional KEGG gene assemblage was homogenized in AS at both the local and regional scale, whereas "Y-A-S" strategies in bacteria were homogenized at the local scale but not the between-site scale. Overall, these results show a clear homogenizing effect of agriculture with respect to multiple aspects of soil taxonomic and functional diversity, though varying by scale. Certain abiotic soil properties showed homogenization in AS at within-site and between-site scales may explain this homogenization, and uniformity of plant cover in croplands likely contribute to the effect. These findings confirm and extend global-scale studies showing homogenization of soil biota in agricultural environments, revealing that effects extend to functional genes and the broad taxonomic spectrum of life – with potential loss of soil ecosystem resilience to environmental change resulting from agriculture.

**Key words:** Land use change; functional gene; microbial homogeneity; Black Soils

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# Challenges and opportunities in interpreting the complex microbial interactions in soil

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**ABSTRACT**

A central challenge in contemporary soil microbiology is to bridge the gap between molecular mechanisms operating at the cellular level and population-level behaviors that emerge in complex soil environments. A key task in this endeavor is to elucidate the eco-evolutionary significance of the vast number of genetic variations that arise in nature. Understanding the environmental conditions under which such variants arise, persist, and gone is essential for correctly interpreting the biological and ecological functions of the corresponding genes.

I will briefly address issues in the so-called social microbiology, as well as the associated challenges and opportunities for enhancing our understanding of soil microbial diversity. Most importantly, I will take this opportunity to highlight key messages drawn from the contributed oral and poster presentations in this session.

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# Experimental drought drives divergent succession of soil microbiota

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## ABSTRACT

Global warming has intensified both the frequency and duration of drought events, posing severe threats to terrestrial ecosystems worldwide[1,2]. Drought limits soil water and nutrient availability[3], suppresses plant productivity[4], and disrupts carbon and nitrogen cycling[5]. Soil microorganisms, which drive these essential biogeochemical processes, are highly sensitive to water limitation[3,6]. However, while many studies have investigated microbial responses to short-term or pulse droughts[7-10], far less is known about how microbial diversity, community composition, and ecosystem functions change under sustained, long-term drought. Most previous research relies on snapshot or short-term experiments, which capture end-point effects but fail to reveal the temporal trajectories that govern microbial adaptation, community reassembly, and ecosystem resilience[7-10]. Understanding these time-resolved dynamics is critical for predicting how ecosystems will respond to progressive and persistent climate stress in the future[11].

To address this gap, we conducted a six-year field drought manipulation experiment in temperate grasslands. The experiment included a control and a drought treatment, in which ambient precipitation was continuously reduced by 50% using automated rainout shelters. Soil samples were collected annually from both drought and control plots to capture temporal trajectories rather than isolated responses.

Our results provides several important insights into the responses of belowground microbial communities to experimental drought. First, a six-year field drought treatment reduced microbial biodiversity and biomass across major kingdom-level soil microbiota, such as bacteria, fungi, and protists (**Fig. 1**). This cross-kingdom pattern of biodiversity decline has not been previously documented in drought-related literature, representing a significant advancement in understanding microbial responses to sustained climatic extremes. Second, long-term drought stress accelerates the temporal succession of soil microbial communities, driving both community compositions and networked communities toward higher divergence. Third, although stochastic processes initially dominated community assembly, their influence declined over time under drought, suggesting that drought acted as a strong deterministic filter (**Fig. 2**). Additionally, drought-driven shifts in community composition and succession down-regulated genes involved in biogeochemical cycling and altered ecosystem functioning (**Fig. 2**). These findings address a critical knowledge gap in understanding belowground responses to drought.

The above findings have important implications for predicting ecological consequences of climate change and for ecosystem management. First, prolonged drought can drive microbial communities to increasingly diverge from contemporary states, raising the likelihood of multiple alternative community configurations and reducing the predictability of future successional trajectories. Also, drought can weaken stochastic influences and strengthen deterministic constraints, allowing communities to converge toward less variable states. Consequently, future microbial community composition may become more constrained and predictable under persistent drought, though they may differ markedly from those observed today. In addition, drought functions as a strong environmental filter that reduces soil microbial biodiversity, which, together with rapid community turnover and declines in beneficial taxa, can substantially weaken ecosystem functions and services and increase ecosystem vulnerability under future drought conditions.

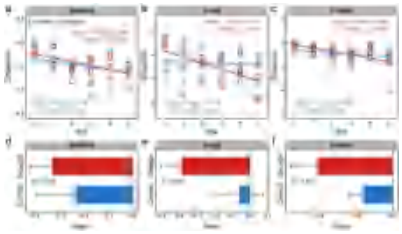


**Fig. 1. The drought effect on soil microbial biodiversity.** (**a**–**c**) Changes of soil microbial diversity over time based on the Shannon index under drought or control. The first year (0) is 2009. (**d**–**f**) Differences in slopes between the drought and control groups. *P* values were based on permutation tests, and adjusted by false discovery rate.

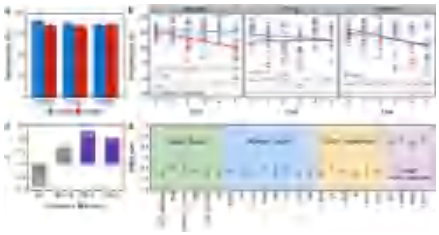


**Fig. 2. Community assembly mechanisms and functional gene responses.** Overall (**a**) and temporal succession (**b**) of stochasticity in shaping bacterial, fungal, and protistan communities based on taxonomic (Sorensen) metrics. Permutation tests were employed to assess the significance of differences in slopes between the drought and control groups, with the results shown as black *p*-values. (**c**) Mantel test (two-sided) between environmental variables and deterministic ratios of bacterial and protistan communities (measured by 1 - stochastic ratio) under drought. *** $p < 0.001$, ** $p < 0.010$, and * $p < 0.050$. PB−T: Total plant biomass. PB−$C_3$: $C_3$ plant biomass. (**d**) The effect sizes of drought on the relative abundances of representative significantly changed (adjusted $p < 0.050$) functional genes.

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# Bacterial cheating is a widespread resource acquisition strategy in soils

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**ABSTRACT**

Soil microorganisms acquire resources by producing extracellular enzymes to break down complex substrates; the depolymerised substrates are then taken up through membrane transporters. It has been widely theorised that some organisms do not produce extracellular enzymes but take up the shareable depolymerised resources, a behaviour often referred to as "cheating". However, genomic evidence for the cheating behaviour in natural soil communities is rare. Here we analyse glycoside hydrolase (GH) genes and sugar-specific ABC transporters in bacterial Metagenome-Assembled Genomes (MAGs) and use the gene count ratio as a cheating index to distinguish uptake-optimised "cheaters" from depolymerisation-optimised "producers". In an 18-month in situ litter-bag experiment in a Mediterranean grassland-shrubland ecosystem, early decomposition stages were dominated by MAGs representing cheaters with higher gene counts for transporters, but lower gene counts for hydrolytic enzymes, whereas later stages were dominated by producers with the opposite pattern. Metatranscriptomic data showed that fungi dominated early stages and encoded far more GH genes than bacteria, suggesting that early-stage cheater bacteria exploit products from fungi-driven depolymerisation. Extending this framework globally, analyses of 29,413 soil MAGs, 5,356 genomes of soil isolates, and 249,311 MAGs of environmental and host-associated bacteria revealed similar uptake-optimised cheater lineages. The cheating index was higher in MAGs from biomes with lower productivity and there was a clear phylogenetic signal. These findings advance our understanding of bacterial cheating as a widespread and enduring strategy in soils, underscoring its global prevalence and potential consequences for ecosystem functioning.

# Analysis of Soil Microbial Community Composition and Diversity Under Different Forest-Medicinal Plant Intercropping Patterns

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**ABSTRACT**

ABSTRACT: *Pinus elliottii* Engelm. is a fast-growing evergreen arbor species native to the southeastern United States. Introduced into China in the 1930s, it has become one of the main afforestation tree species in the hilly areas of southern China. However, long-term monoculture plantations of this species can easily lead to soil nutrient depletion and microbial community imbalance, highlighting the need to improve stand quality and develop high-efficiency economic forests. 【Objective】 This study aimed to identify suitable intercropping patterns for understory medicinal plant in *Pinus elliottii* Engelm. forests, thereby providing a scientific basis for management decisions. 【Method】 Three intercropping patterns were tested: *P. elliottii-Ficus simplicissima-Spatholobus suberectus* (PHS), *P. elliottii-Alpinia oxyphylla-S. suberectus* (PAS), *P. elliottii-Amomum villosum-S. suberectus* (PSA), with a pure *P. elliottii* forest serving as control (CK). Soil nutrient dynamics and enzyme activities were determined, and rhizospheric microbial communities were analyzed using high-throughput sequencing. 【Result】 Under the same intercropping pattern, soil nutrients in (0, 20] cm layer were higher than those in the [20, 40) cm layer, except for total nitrogen (TN) under PSA pattern. In the (0, 20] cm layer, all three intercropping patterns significantly reduced amylase activity compared to CK ($p< 0.05$). The PHS pattern significantly increased acid phosphatase and urease activities while decreasing nitrate reductase activity ($p< 0.05$). In the PAS pattern, acid phosphatase, neutral protease, and urease activities were significantly enhanced, with urease activity significantly higher in (0, 20] cm than in the [20, 40) cm layer. High-throughput sequencing revealed interactions among intercropping patterns, soil properties, and microbial communities. Intercropping significantly affected the structure, composition, and diversity of both rhizosphere bacterial and fungal community. Molecular ecological network analysis indicated that the PHS pattern enhanced the stability and complexity of rhizosphere bacterial community. Redundancy analysis (RDA) identified organic carbon (SOC) and total nitrogen (TN) as key drivers of microbial variation. Random forest and LefSe analyses further identified key taxa, such as *Acidibacillus* and *Thermosporothrix*, as significantly associated with the intercropping effects. Different patterns may affect soil properties by increasing the relative abundances of specific taxa, thereby enhancing plant growth and stand quality. Functional prediction suggested that microorganisms may improve soil quality and promote plant growth by regulating gene responses in "Metabolism of terpenoids and polyketides" and "Urea Cycle" pathways, as well as by secreting enzymes such as ferredoxin hydrogenase and beta-mannosidase. 【Conclusion】 Different forest-medicinal plant intercropping patterns affect soil quality and enzyme activities, potentially via regulating microbial community diversity, the abundance of specific taxa abundance, functional gene response, and enzyme secretion.

# Wetland Age and Seasonality Drive the Succession of Active Methanotrophs in Constructed Wetlands

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**ABSTRACT**

The Global Methane Pledge, endorsed by more than one hundred nations, highlights the urgent need to reduce $CH_4$ emissions to achieve the net-zero target by 2050. Wetlands function as effective carbon sinks but are also major natural sources of $CH_4$. Constructed wetlands (CWs) are increasingly utilized as nature-based solutions, yet the microbial mechanisms that regulate $CH_4$ oxidation, the primary sink for methane in soil, remain insufficiently characterized.

This study investigated how wetland age and seasonality influence $CH_4$ oxidizing communities in three CWs of different ages located in subtropical Taiwan. We used DNA-based stable isotope probing (DNA-SIP) combined with *pmoA* gene sequencing to identify potentially active methanotrophs during both summer and winter. We also analyzed key edaphic properties to comprehensively define the environmental drivers of community transitions.

Results showed that $CH_4$ oxidation potential was generally higher in winter but exhibited a functional decline as the wetlands aged. The SIP analysis revealed a clear shift in dominant active methanotrophic families, transitioning from *Methylocystaceae* in younger wetlands to *Methylomonadaceae* in older systems. Soil nutrients, salinity, and sulfate concentration were identified as important drivers structuring this ecological shift across wetlands of varying age.

These findings illustrate how wetland age and seasonality act as important drivers of compositional and functional succession within active methanotrophic communities. This mechanistic understanding provides crucial implications for optimizing CW design and management to enhance $CH_4$ oxidation potential, thereby strengthening their role in mitigating greenhouse gas emissions.

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# Leveraging the root economics space: outsourcing rice varieties outperform do-it-self strategies under stress

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**ABSTRACT**

Salinity stress is a major constraint to global rice production. Plants employ two primary strategies to cope with stress: the 'do-it-self' (DIS) strategy reliant on intrinsic genetic capacity, and the 'outsourcing' strategy involving the recruitment of beneficial microbes. It remains unclear which strategy confers a greater advantage for stress resistance within the same species. To investigate this, we conducted a controlled greenhouse pot experiment comparing 18 rice varieties grown in saline-alkaline soil. By analysing root spatial architecture and plant growth parameters, we assessed the contribution of each strategy. We further employed amplicon sequencing, metagenomics, and ecological network analysis to characterize the associated rhizosphere microbiota. Results showed that 'outsourcing' plants exhibited superior growth under stress. Their root microbiome was enriched with core functional taxa, including *Hydrogenophaga, Brevundimonas*, *Ideonella*, *Aquimonas*, *Methylomonas*, and *Phenylobacterium*. Concurrently, the microbial networks in this group displayed greater topological complexity, with more nodes, edges, and keystone taxa, indicating enhanced stability. In contrast, the rhizosphere of "DIS" plants was enriched for bacteria such as *Paenisporosarcina* and *Porphyrobacter*, and their microbial networks featured a higher proportion of positive correlations and more positive interactions bridging the rhizosphere and endosphere compartments. Metagenomic functional analysis revealed a significant enrichment of genes involved in antioxidant response, synthesis of osmolytes, ion homeostasis, and membrane stability in the "outsourcing" group. Furthermore, the microbial genomes in this group contributed to ammonium accumulation, carbon fixation, and phosphorus solubilization. Our study, framed within the root economics space concept, demonstrates the critical role of the rhizosphere microbiome in crop stress resistance, identifies key taxa and their metabolic potential, and provides a theoretical foundation and candidate resources for developing microbial inoculants to enhance crop resilience.

**Keywords:**Root economics space; Rice; Saline-alkaline soil; Stress; Microbial ecological network; Metagenomics

# Carbon monoxide metabolism as a driver of volcanic soil colonisation

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**ABSTRACT**

Volcanic eruptions reset ecosystems to barren landscapes, initiating microbial colonisation that often relies on trace gases such as carbon monoxide (CO) for survival in nutrient-poor conditions. This study investigates CO metabolism in volcanic soils from these environments. Metagenomics and enrichment strategies targeting carboxydovores - bacteria capable of oxidising low-to-ambient CO concentrations - were employed to isolate two novel strains (Dawson et al., 2025). Whole-genome sequencing and CO consumption assays revealed distinct mechanisms regulating CO metabolism during transitions from heterotrophy to starvation, providing insight into microbial survival in extreme environments. Both strains contain *coxMSL* genes, which encode CO dehydrogenase responsible for CO oxidation, along with uncharacterised accessory genes. This work also explores the active microbes consuming CO in volcanic soils using stable isotope probing (SIP) with $^{13}CO$ as the substrate. SIP has shown that CO was primarily incorporated into Pseudomonadota. Further metagenome-assembled genomes from the heavy fractions show the presence of genes encoding for the CO dehydrogenase, responsible for the oxidation of CO. These findings emphasise the significance of CO metabolism in early soil formation and bacterial community establishment, presenting novel model strains to further investigate microbial adaptations in volcanic ecosystems.

**Acknowledgments**

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# Maize//Soybean Intercropping Enhances Soil Multifunctionality in Low-fertility Red Soil and Its Response to Biodiversity Effects

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**ABSTRACT**

The enhancement of soil multifunctionality (SMF) in medium- and low-fertility red soils is considered crucial for improving crops productivity and agriculture sustainable development in the southwestern plateau region, China. Rational intercropping plays an important role in enhancing crop yield and improving soil fertility in red soil. To study the effects of intercropping on soil multifunctionality, and to explore the relationship between soil multifunctionality and biodiversity effects under intercropping in red soil, a seven-year consecutive field experiment was conducted. Two planting patterns maize monoculture (MM) and maize//soybean intercropping (IM)-were compared under four phosphorus (P) fertilizer application gradients (0, 60, 90, and 120 kg $P_2O_5$ $ha^{-1}$). Changes in individual soil functions and SMF under intercropping system, The components of the biodiversity effect (BE), and their response to P application rate were systematically examined. The results showed that, compared to maize monoculture, SMF was significantly enhanced by maize//soybean intercropping across the four P gradients, with an average increase of 46.21%. The highest increase of 176% was observed at the P90 level. Specifically, the individual soil functions for nutrient cycling, production function, and water conservation were significantly enhanced by 58.12%, 56.04%, and 22.47%, respectively. Compared to the corresponding monoculture, maize//soybean intercropping significantly increased the biodiversity effects (BE), in which the net effect (NE) and complementarity effect (CE) of the intercropping BE were significantly increased with the rising of P levels, while the selection effect (SE) was reduced. The CE was identified as the primary factor driving the improvement in SMF. A highly significant positive correlation was observed between SMF and NE and CE. Key influencing factors were identified as soil available phosphorus (AP), soil microbial biomass phosphorus (MBP), soil ammonium nitrogen ($NH_4^+$-N), soil organic carbon (SOC), soil bulk density (BD), and soil microbial biomass carbon (MBC). In conclusion, maize//soybean intercropping offered significant advantages on low-fertility red soil in terms of increasing maize yield, enhancing soil multifunctionality, and strengthening biodiversity effects. The intercropping advantage was found to be optimal at P application rates of 60-90 kg $P_2O_5$ $ha^{-1}$, achieving a dual benefit of high crop yield and improved ecological service functions. Maize and soybean intercropping with optimizing fertilization in red soil is an effective practice both for improving soil quality and soil health, and promoting sustainable agricultural development.

**Keywords:** Maize//soybean intercropping; Low-fertility red soil; Soil multifunctionality; Biodiversity effect

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# Eco-evolutionary patterns of microbial engine that drives reduction of greenhouse gas

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**ABSTRACT**

Microbe is considered the engines that drive Earth's biogeochemical cycles, and play a pivotal role on greenhouse gas emission. However, it has been highly debated but rarely tested of eco-evolutionary mechanism underlying the production and reduction of greenhouse gas emission. In this presentation, I will take aerobic methane-oxidizing bacteria (MOB methanotrophs) as an example to show how novel MOB is generated and MOB community is maintained in an eco-evolutionary context. The focus will be niche differentiation vs extraordinary plasticity of MOB. The assembly of MOB community can be considered as a net result of long-term ecological and evolutionary adaptation to historical environmental variables. These variables could be largely predicted with time- and spatial-dependent patterns. The numerically dominant taxa are thus expected to have the highest physiology plasticity as environmental variables often fluctuate constantly and widely, but most importantly in a manner of being predictable. It thus implies the certain environmental factors could select for particular taxa, and microcosm experiment can inform global ecological problems. It is noteworthy that the generation and development of the individual microbial taxa cannot be achieved overnight and seems to be intractable under in situ field conditions. I would like to show how environmental factors can select particular methane oxidizers at ecosystem-level. The molecular evidence of MOB metabolisms will also be presented showing how ecosystem sustainability is supported by the population dynamics of microbial fecundity, survival, and mortality in complex soil.

**Keywords:** carbon neutrality, microbial diversity, evolution, ecology and taxonomy

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# The impact of microbial-mediated crop residues and their humification products on soil organic matter transformation

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**ABSTRACT**

Given that microbial mediated input of cropresidues and their humification products may be more conducive to the transformation and sequestration of soil organic matter, this study aims to use $^{13}C^{15}N$ double labeling tracing technology in incubation experiments to quantify the differences in the fate and distribution of C and N from crop residues and their decomposition products under the mediation of different exogenous microorganisms in soil organic matter (SOM) and dissolved organic matter (DOM). The study utilized exogenous microorganisms including *T. reesei*, *T. harzianum*, *P. chrysosporium*, and *B. subtilis*, as well as a combination treatment of *T. harzianum*, *P. chrysosporium*, and *B. subtilis*. The study also reveals variation patterns of soil active organic carbon and humic carbon components. The main conclusions are as follows:

The addition of fungi was more favorable than bacteria in mediating the increase in soil SOM contribution of crop residues derived C and N. *Trichoderma* spp. treatments were more adept at mediating crop residues derived dissolved organic carbon, and fungi were more likely to stimulate soil production of dissolved nitrogen. Although the combination microbial treatment was most effective at translational immobilization of crop residues in SOM, the *T. reesei* treatment had the best ability to increase soil organic carbon content by mediating crop residues translational immobilization with the lowest depletion of SOM. Additionally, fungi were more effective than r-strategy microorganisms in increasing labile organic carbon and humic carbon fractions in soil.

Fungi mediated humification products was significantly better than bacterial and no microbe mediated for translational immobilization in soil, and fungal treatments contributed more to DOM and stimulated soil deriving dissolved nitrogen. The *T. reesei* treatment was most effective in immobilizing carbon and nitrogen derived from humification products. Fungi mediated humification products was superior to bacteria in boosting labile organic carbon and humic acid fractions. Combination treatments increased fulvic acid carbon and reduced PQ values early in the experiment, while fungal treatments increased fulvic acid carbon in later phases.

These conclusions provide a theoretical basis for microbial regulation of farmland management to improve SOM transformation and humification, offering practical guidance for agricultural production and soil carbon sequestration.

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# Regulation of methane oxidation in natural grassland by animal urine addition gradients

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## ABSTRACT

Natural grasslands occupy ~40% of Earth's terrestrial surface and serve as the primary grazing areas for ruminant livestock. A single urination event from a sheep releases ~0.50 L of urine (Selbie et al., 2015), and daily urination frequency varies among individuals. Consequently, 70–95% of the nitrogen ingested by animals is returned to the soil via urine patches, which become hotspots of nitrogen transformation. Previous studies have focused on urine patches as strong sources of $N_2O$ emissions and on the microbial mechanisms driving ammonia oxidation (Schirmann et al., 2019; Zhu et al., 2021). However, this acute perturbation rapidly alters soil physico-chemical micro-environments and simultaneously affects the activity and community structure of soil methanotrophs. Systematic knowledge of the thresholds at which urine patches switch from methane absorption to emission is still lacking, especially regarding the response of soil methanotrophs to urine deposition. Elucidating these microbial mechanisms is therefore essential.
DNA-based surveys indicate that methanotrophic communities respond weakly to short-term environmental fluctuations (Nannipieri et al., 2019), making it difficult to capture instantaneous functional changes. RNA-Seq (transcriptome sequencing) is a recently developed deep-sequencing technology that detects global transcriptional activity at single-nucleotide resolution, enabling the identification of novel and rare transcripts, alternative splicing sites and coding-sequence SNPs (cSNPs), thereby providing high-resolution information on gene expression (Täumer et al., 2022). Consequently, the present study integrates *pmoA*-gene sequencing with transcriptome data to systematically unravel the microbial mechanisms driving methane oxidation beneath urine patches in natural grassland soils. Such knowledge will improve estimates of methane emissions and atmospheric concentration trends, supplying critical data for greenhouse-gas mitigation strategies.

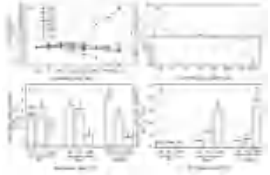
**Materials and Methods**
The soil was collected from an ungrazed natural grassland on the Loess Plateau (37.12°N, 106.82°E), and fresh urine was obtained from Tan sheep, a locally common grazing breed (urine nitrogen concentration: 10.90 g N $L^{-1}$, equivalent to 545 kg N $ha^{-1}$). In the laboratory, a gradient incubation experiment was conducted with urine addition volumes of 0 (No urine, NU), 0.1 (Lowest urine, LU), 0.2 (Low urine, LU1), 0.3 (Field Urine, FU, representing the typical urine volume excreted by sheep in the field), 0.4 (Medium urine, MU), 0.5 (Medium-high urine, MHU), 0.7 (High urine, HU), and 1 mL (Ultra-high urine, UHU), with four biological replicates per treatment. Following the method described by Wang et al. (2022), the methane concentration in the headspace of the incubation bottles was determined y at 0 h, 2 h, and on Days 1, 3, 5, 7, 10, and 14 by gas chromatograph (GC-7890A, Wilmington, USA). The atmospheric methane oxidation potential (atmMOP) was characterized by calculating the methane oxidation rate based on the change in methane concentration between 0 h and Day 14.
Based on the results of methane oxidation potential, soil samples from the NU, FU, and UHU treatments were selected for analysis of methanotroph abundance and diversity. Total DNA of soil sample was extracted from 0.5 g fresh soil using the Mag-Bind® Soil DNA Kit (Omega Bio-tek, Norcross, GA, U.S.A.) according to the manufacturer's instructions. For the 16S rRNA and pmoA gene, the primers 515F/907R (Stubner, 2002) and A189F/mb661R (Costello and Lidstrom, 1999) were used to determine abundance of methanotrophs using real-time quantitative PCR (qPCR). The diversity of methanotrophs under urine influence was assessed by sequencing the *pmoA* gene (primers A189F/mb661R) on the Illumina MiSeq platform
Based on the methane oxidation trends and variations in methane oxidation potential across treatments, soil samples from the NU, FU, and UHU treatments incubated for 6 days (when methane concentration change was most pronounced) were selected for metatranscriptome sequencing, with four replicates per treatment. Total RNA was isolated with the RNeasy PowerSoil Total RNA Kit (Qiagen, Germany). Strand-specific mRNA libraries were prepared using the Illumina Stranded mRNA Prep, Ligation Kit (Illumina, USA) and sequenced on the NovaSeq 6000 S4 Reagent Kit v1.5 (300 cycles). Raw FASTQ files were quality-trimmed with fastp (https://github.com/OpenGene/fastp) (Chen et al., 2018). Clean reads were mapped to the Unigene set and expression values were calculated as RPKM (reads per kilobase of References per million mapped reads) with RSEM (http://deweylab.biostat.wisc.edu/rsem/).
Differences among urine-addition gradients at the same incubation time were tested by one-way ANOVA. Statistical comparisons of soil physicochemical properties and measured values of 16S rRNA and *pmoA* gene abundances were performed using one-way ANOVA, with means compared by Duncan's post-hoc test. Pearson correlation among atmospheric methane oxidation potential, soil physicochemical properties, and methanotroph abundance was estimated using R software.

**Results and Discussion**
***Effect of urine addition on methane oxidation trend and methane oxidation potential***
Methane concentrations exhibited distinct trends across the urine-addition gradient. In NU treatment, $CH_4$ was completely oxidized, whereas the UHU treatment switched from a $CH_4$ sink to a pronounced source after Day 5 (Fig.1A). The atmMOP of UN was 0.11±0.001 ng g_1 h_1 (dry weight soil, *d.w.s.*). Treatments with LU1, LU2, FU and MU, soil also oxidized $CH_4$, although at lower rates. In contrast, treatments with MUH, HU and UHU showed progressively increasing net $CH_4$ release with higher urine volumes (Fig.1B). Treatment with the FU, soils acted as a weak atmospheric $CH_4$ sink, consistent with observations from Nandi County, Kenya (Tully et al., 2017) and a desert steppe in Inner Mongolia (Jiang et al., 2012). Studies reporting $CH_4$-uptake inhibition (Wu et al., 2020) align with our UHU treatment (Fig.1).
***Effect of urine addition on methanotroph abundance***
Based on the methane oxidation potential observed across the urine addition gradient, the NU, FU, and UHU treatments were selected for subsequent analysis. Urine amendment significantly influenced the abundances of total bacteria and methanotrophs in contrasting patterns (Fig.1C,D). Specifically, urine addition decreased *pmoA*-based methanotroph abundance, with this reduction becoming progressively more pronounced among treatments after 7 days of incubation. By Day 7 and Day 14, methanotroph abundance in the UHU treatment was significantly lower compared to both the NU and FU treatments (Fig.1C). Conversely, quantification of 16S rRNA genes indicated that urine addition, particularly under the UHU treatment, led to a significant increase in total bacterial abundance. Although total bacterial abundance remained unaffected by the urine gradient at 2 hours post-incubation, the UHU treatment showed significantly elevated bacterial abundance relative to the NU and FU treatments by Day 7 and Day 14 (Fig.1D).
Methanotroph abundance can respond to environmental changes more rapidly than shifts in methanotroph diversity (Zheng et al., 2012), a pattern consistent with our observations. Methanotroph abundance declined with time and urine dose (Fig.1C), reflecting the transition from a $CH_4$ sink to a $CH_4$ source. Total bacterial abundance increased with incubation time and urine dose (Fig.1D), likely because urine addition progressively altered soil pH, $NH_4^+$-N and TC (Fig.2A). Following urine addition, both soil pH and $NH_4^+$-N concentration increased sharply, showing significant negative correlations with atmMOP (Fig.2A). This suppression may be attributed not only to osmotic stress induced by urine salts under elevated pH conditions, which nonspecifically inhibits methanotroph activity, but also to the conversion of $NH_4^+$ to ammonia ($NH_3$). Due to their similar molecular structures, $NH_3$ competes with $CH_4$ for the active site of methane monooxygenase, leading to competitive or non-competitive inhibition of methane oxidation (Gulledge et al., 1998). In addition, $NH_4^+$-N and TC provided nutrients for the growth of other microorganisms, resulting in an increase in total bacterial abundance. The increased relative abundance of the phylum Firmicutes supports this inference (Fig.2B).
***Impact of urine addition on methanotroph composition***
High-throughput sequencing of the *pmoA* gene revealed that, along the urine-addition gradient, the methanotroph community was dominated by USCγ (USCγ + JR3), accounting for 94.97–99.87% of all *pmoA* reads. Notably, the UNU treatment showed a significant increase of the relative abundance of *Methylocaldum* on Day14, reaching 4.13%, far higher than other treatments (Fig.3). Therefore, it can be concluded that the changes in community composition are caused by a significant decrease in the relative abundance of USCγ (Wang et al., 2022).
**Gene expression underlying methane oxidation and methanogenesis in response to urine addition**
After six days of incubation, metatranscriptome data (RPKM) fully revealed the gene expression profiles related to methane oxidation and methanogenesis under NU, FU, and UHU treatments (Fig.4). In the NU, transcripts of aerobic methane oxidation—*pmoCAB*, *xoxF*, *fae* and *fdh*—were abundant. Nearly all known aerobic methanotrophs possess the pMMO-encoded *pmoA* gene (Murrell et al., 2010); Accordingly, significantly higher expression levels of *pmoA* and *XoxF* transcripts were detected in the NU compared to the FU and UHU treatments, with no methanogenic genes detected. This gene expression profile confirms the dominance of aerobic oxidation, explaining the net soil $CH_4$ uptake under these conditions (Fig. 4A). Furthermore, the atmMOP under the NU treatment is consistent with and extends our previous regional findings, wherein soil factors (soil moisture and nitrogen) were shown to govern the atmMOP by directly or indirectly regulating methanotroph abundance (Wang et al., 2022).
At the FU treatment, the high expression of *hdrD* (involved in sulfate-coupled anaerobic methane oxidation) (Alperin et al., 1985) along with *pmoA* and *xoxF* transcripts indicates concurrent aerobic and anaerobic methane oxidation. Detection of *Mer* and *ackA* transcripts also suggests active hydrogenotrophic and aceticlastic methanogenesis (Fig. 4B). Nevertheless, the soil remained a net methane sink, as methane oxidation exceeded methanogenesis. This can be explained by urine-induced micro-zone differentiation: aerobic methane oxidation continued at the oxygenated patch edges, while strictly anaerobic zones (e.g., patch centers or soil aggregates) favored anaerobic methane oxidation and methanogenesis (Sexstone et al., 1985). Overall, methane oxidation—integrating both aerobic and anaerobic pathways—slightly surpassed methane production, thereby sustaining the soil's methane-sink function (Le Mer and Roger, 2001).
In contrast, the treatment of UHU showed elevated $CH_4$ concentrations. *pmoA* and *xoxF* transcripts were absent, and only the methylotrophic methanogenesis genes *mtmB* and *mtrC* were expressed (Fig.4C). *mtmB* encodes a trimethylamine-inducible methyltransferase characteristic of novel Euryarchaeota methanogens, and both *mtmB* and *mtrC* are also present in the proposed methanogenic pathway of Verstraetearchaeota (Vanwonterghem et al., 2016). With increased urine application, the urine patch rapidly establishes an anaerobic microenvironment. Concurrently, ammonium ($NH_4^+$) generated from urea hydrolysis competitively inhibits methane monooxygenase activity (Isobe et al., 2020). Moreover, urine contains small organic molecules—including methanol, methylamines, and acetate—that act as direct substrates for methylotrophic and aceticlastic methanogens, enabling rapid methane production. Enhanced expression and activity of key methanogenic enzymes encoded by genes such as *mtmB* and *mtrC*, further drive methanogenesis, ultimately shifting the soil from a methane sink to a net methane source (Bueno de Mesquita et al., 2023).
**Conclusion**
Compared with NU, the FU treatment reduced atmospheric $CH_4$ oxidation capacity by 80.74%, yet the soil still functioned as a weak $CH_4$ sink. In contrast, the UHU treatment shifted the soil from a sink to a source. These outcomes were primarily driven by changes in methanotroph abundance and differential expression of key genes regulating $CH_4$ oxidation and emission. In the FU treatment, net $CH_4$ uptake occurred because the combined methane oxidation flux (aerobic+anaerobic methane oxidation) exceeded the concurrent methane production flux (hydrogenotrophic and aceticlastic methanogenesis). In the UHU treatment, methylotrophic methanogenesis was strongly stimulated while $CH_4$ oxidation was nearly completely suppressed, resulting in net $CH_4$ emission.
**Keywords:** Grasslands, Methane oxidation, Urine addition, USCγ **Introduction**

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Fig.1 Trend of methane oxidation potential over time under different gradient urine additions(A), atmosphere $CH_4$ oxidation potential(B), abundance of total bacteria and methanotrophs estimated by qPCR using *pmoA* (C) and 16S rRNA (D) gene.



Note: Different lowercase letters within the same row indicate significant differences ($P < 0.05$) among urine-addition gradients for the given index; values lacking lowercase letters show no significant differences ($P > 0.05$) under different urine-addition treatments.

Fig.2 Pearson correlation analysis between atmMOP and relative abundance of methanotrophs, soil properties (A), and soil microbial community composition estimated by 16S rRNA gene on phylum level amplicon sequencing with NU, FU and UHU at different incubation time (B).



Note: * indicates significance at $P < 0.05$, ** indicates significance at $P < 0.01$.

Fig.3 Soil methanotroph community composition estimated by amplicon sequencing of the *pmoA* with NU, FU and UHU.

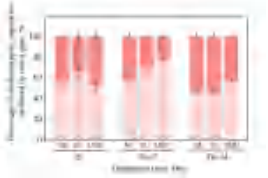


Fig.4 Mechanisms by which NU, FU and UHU of urine regulate methane oxidation processes.



# Effects of Different Straw Return Methods on Soil Microbial Community Structure and Diversity

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**ABSTRACT**

In response to the slow increase in soil organic matter in the black soil farmland of Northeast China, a field positioning experiment was conducted on black soil farmland in Xing'an League Ulanhot, Inner Mongolia. A split-plot design was adopted, with two straw incorporation depths 0–20 cm (Q) and 0–40 cm (S)) as the main plots and four straw input amounts 0 (CK), 1/3 (JG1), 2/3 (JG2), and full amount (JG3)) as the subplots, to analyze the effects of straw return methods on soil microbial community composition. The results showed that: (1) Compared with CK, all treatments significantly increased the contents of SOM, AK, AP, and TN, and these values increased with the straw return amount. Meanwhile, soil pH and $NH_4^+$-N content were significantly reduced, with soil pH gradually decreasing as the application rate increased. The shallow incorporation treatment performed better than the deep incorporation treatment. (2) In terms of microbial community, under shallow incorporation, the abundances of Proteobacteria and Basidiomycota increased with the application rate, while the abundance of Ascomycota decreased. Compared with deep incorporation, shallow incorporation increased the abundances of Actinobacteria and Chloroflexi but decreased the abundance of Proteobacteria. (3) Regarding microbial diversity, the microbial Chao1 index initially increased and then decreased with increasing application rate, while the Simpson index increased with the application rate. (4) Random forest analysis revealed that soil pH was the key environmental factor influencing bacterial diversity, while fungal diversity was mainly affected by soil SOM. In summary, different straw return methods can help improve basic soil physicochemical properties and enhance microbial diversity, promoting a shift from K-strategists to fast-responding r-strategists. In practical production, shallow incorporation with full straw return is recommended, providing a theoretical basis for microbial organic carbon sequestration, conservation, and sustainable development of black soil farmland.

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# Tropical rubber plantations' expansion alters multiple ecosystem functions and C storage

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**ABSTRACT**

The global demand for natural rubber has driven substantial expansion of rubber plantations since the last century, with over 2 million hectares established in the most recent decade. Southeast Asia remains the primary region for rubber cultivation, often at the expense of other land uses. While rubber farming has raised farmers' incomes, it has also altered local habitat ecology and ecosystem functions. Yet studies on the impact of rubber plantations on ecosystem functions are limited, and a comprehensive synthesis is lacking. To address this gap, we conducted an inclusive review of the ecosystem functions of rubber plantations, focusing on soil carbon storage, aboveground biomass (AGB) and belowground biomass (BGB), litter production and decomposition, respiration, and biodiversity (plants, animals, soil fauna, and microbes). We compared ecosystem functions in monoculture rubber plantations with those in forests, as forest conversion to RP is common in the tropics, and most rubber plantation studies use forests as References ecosystems. Our findings indicate that rubber plantations generally exhibit lower ecosystem functions than forests. The adverse effects on several components of ecosystem function are pronounced. AGB, BGB, and plant diversity show declines exceeding 55% and these impacts persist across plantation ages.

**Keywords:** *Hevea brasiliensis*, Soil organic carbon, Microbial community, Soil nutrient cycling.

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# Cobamide Auxotrophy and Unexpected Cobamide Synthesis Potential in Organohalide-respiring Dehalococcoidia

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**ABSTRACT**

Cobamides (Cbas) are structurally diverse, vitamin $B_{12}$ family enzyme cofactors that fulfill essential microbial metabolisms such as methanogenesis and organohalide respiration. The best-studied cobamide is cobalamin (Cbl), which carries 5,6-dimethylbenzimidazole (DMB) as the lower ligand. Because *de novo* Cba biosynthesis is restricted to a subset of bacteria and archaea, environmental Cba pools in soils and sediments are largely governed by microbial cross-feeding, salvage, and remodeling. Such community-level cofactor supply is particularly important for organohalide-respiring bacteria (OHRB), which reply on specific Cbas to enable the catalysis of carbon-halogen bond-cleaving reductive dehalogenase (RDases). In contaminated vadose-zone and aquifers, OHRB can form reactive biobarriers at the groundwater-soil interface to detoxify chlorinated contaminants and reduce their upward migration flux from groundwater into overlying soils. Yet, how Cba bioavailability constrains OHRB activity remains poorly understood. Here, we demonstrate the strict dependence on external Cbl supply to sustain *Dehalogenimonas etheniformans*, an organohalide-respiring lineage affiliated with the class *Dehalococcoidia*. Substitution of the lower ligand with a DMB analogue compromised, and in some cases completely inactivated *D. etheniformans*, suggesting pronounced cofactor selectivity that can translate into ineffective biobarrier performance *in situ*. Notably, 5-hydroxybenzimidazolyl-cobamide ([5-OHBza]Cba) did not sustain *D. etheniformans culture*, but the ability of *D. etheniformans* to respire a chlorinated ethene (e.g., tetrachloroethene) into non-toxic ethene was fully restored with the addition of DMB. This phenotype aligns with genomic predictions, suggesting that *D. etheniformans* uses CbiZ-mediated remodeling pathway to convert an unusable cobamide into Cbl. By analyzing available genomes across the class *Dehalococcoidia*, we further show that *Dehalogenimonas formicexedens* and *Dehalogenimonas* sp. strain W encode nearly the full set of genes for *de novo* corrin ring biosynthesis. Remarkably, *D. formicexedens* is, to our knowledge, the only formally named non-*Bacillota* bacterium identified to harbor a complete *bza* gene set for DMB biosynthesis. The Cba-related genes in *D. formicexedens* are partitioned into three loci, corrin ring synthesis, cobinamide salvage, and DMB synthesis, each positioned directly downstream of a Cbl riboswitch, implying coordinated regulation and potential to produce Cbl *de novo* from glutamate. Collectively, our results correlate Cba structural feature (i.e., lower base) with the ecological control of soil and subsurface microbiomes as well as the effectiveness of natural attenuation of chlorinated solvents at contaminated sites. Through targeted-manipulation of indigenous Cba/DMB producers, it is possible to maintain robust dechlorination activity and limit the upward flux of chlorinated contaminants from groundwater into soils. : soil microbiome

**Keywords:** soil microbiome, cobamide, organohalide-respiring bacteria

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# Crop rotation and residue management enhance banana health by enrichingcore antagonistic microbes

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## ABSTRACT

Banana *Fusarium* wilt (Panama disease), caused by the soil-borne pathogen *Fusarium oxysporum* f. sp. *cubense* tropical race 4 (*Foc*TR4), is a devastating disease that threatens global banana production. This study combined eight years of field trials with complementary pot experiments, multi-omics analyses, and functional validation to systematically investigate the mechanisms through which pepper-banana and eggplant-banana rotations—together with the incorporation of rotation crop residues—shape the soil core microbiome, enhance microbial diversity, enrich antagonistic taxa, and suppress *Fusarium* wilt.

We found that pepper and eggplant rotations selected nine rotation-specific core antagonistic microorganisms through soil legacy effects. Pepper rotation enriched eight of these taxa, while eggplant rotation enriched one.

These core antagonistic communities stably persisted into the subsequent banana cropping season, reducing the disease incidence from 53% in monoculture control to 31% (pepper rotation) and 28% (eggplant rotation), respectively (Figure 1). Integrating traditional culture-based methods with high-throughput sequencing identified *Bacillus* and *Pseudomonas* as core functional taxa enriched under rotation. Metabolite extracts and volatile organic compounds from these taxa strongly inhibited *Foc*TR4 growth.



Figure 1 Conceptual model showing the targeted enrichment of crop-unique antagonistic core microbiota by distinct rotation systems for wilt disease suppression in banana (Hong et al., 2023, *New Phytologist*).

Further experiments involving residue incorporation demonstrated that adding pepper and eggplant residues significantly increased soil available phosphorus. Beyond enhancing microbial diversity, residue amendment enriched antagonistic taxa such as OTU180 (*Rhizomicrobium*) and OTU187 (*Gp4*) by remodeling the rhizosphere, contributing to a functional microbial defense barrier that reduced disease incidence below 20% in follow-up pot trials. Structural equation modeling identified available phosphorus as a critical mediator linking residue incorporation to pathogen suppression, operating indirectly through increased abundance of core antagonistic microbes (Figure 2).



Figure 2 The model diagram revealed a potential mechanism by which incorporating pepper and eggplant residues into the field suppresses soil-borne pathogens (Hong et al., 2025, *Applied Soil Ecology*).

This work provides the first systematic analysis of the assembly and functional dynamics of core antagonistic communities in rotation systems, and demonstrates that residue-driven enhancement of soil microbial diversity can further boost the disease-suppressive capacity of rotations. Key innovations include: (1) a framework for identifying rotation-specific core antagonistic microbiomes and characterizing the temporal persistence and spatial stability of their legacy effects; and (2) elucidation of a novel phosphorus-mediated pathway, through which residue-microbe interactions enhance disease suppression by increasing microbial diversity. The proposed integrated model of "rotation screening—residue enhancement—microbiome regulation" provides a practical framework for sustainable, disease-resilient cropping systems.

**Keywords:** crop rotation, residue management, core microbiome, microbial diversity, disease suppression **References**

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Hong, S., Yuan, X., Jia, Z., and Ruan, Y. (2025). Enhancing banana health with key antagonistic taxa by crop residue-driven strategies. *Applied Soil Ecology* 210, 106046

# Effects of Perennial and Annual Plant Life Forms on Rhizosphere Bacterial Communities in Saline–Alkali Desert Soils

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**ABSTRACT**

Saline–alkali soils in arid and semi-arid regions severely constrain plant growth and soil microbial functioning, but the mechanisms underlying rhizosphere bacterial community assembly driven by different plant life remain unclear. Here, we investigated four representative halophytes in desert saline–alkali habitats of Manas County, Xinjiang, China, including two annual herbs (*Halogeton glomeratus* and *Suaeda glauca*) and two perennial shrubs (*Haloxylon ammodendron* and *Krascheninnikovia ceratoides*). Rhizosphere soils were analyzed for physicochemical properties (pH, electrical conductivity (EC), soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK)) and bacterial communities using 16S rRNA high-throughput sequencing. The results showed that (1) perennial shrubs exhibited significantly higher SOC and TN contents, as well as higher bacterial α-diversity (ACE, Chao1, Shannon) and lower Simpson indices, than annual herbs ($P < 0.05$), indicating more diverse and stable rhizosphere bacterial assemblages. Community composition profiling revealed perennial shrubs more consistent and structured microbial communities, annual herbs exhibit greater heterogeneity in their rhizosphere microbiomes. (2) Redundancy analysis (RDA) and correlation heatmaps identified SOC, TN, and pH as the dominant environmental drivers of rhizosphere bacterial diversity and community composition, with taxon-specific responses of major phyla (e.g., *Actinobacteriota*, *Proteobacteria*, *Chloroflexi*, *Gemmatimonadota*, *Firmicutes*, *Acidobacteriota*) to nutrient status and pH in saline–alkali soils. (3) Piecewise structural equation modeling (SEM) further revealed that perennial and annual plant life forms influence rhizosphere bacterial diversity and structure via both direct and indirect pathways. The direct effect (standardized effect=0.99) was predominant in shaping bacterial diversity, while plant life forms mainly affected bacterial community structure through indirect effects (standardized effect = 0.34) mediated by soil physicochemical properties, particularly TN, SOC, and pH. These findings highlight that plants shape their rhizosphere microbiota through direct selective recruitment and indirect modification of soil physicochemical properties. Our results enhance understanding of plant functional type-soil-microbe interactions in saline–alkali ecosystems and emphasize the ecological value of perennial shrubs for microbial-mediated restoration and sustainable management of saline–alkali lands.

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# Repeated Drying-Rewetting Cycles Maintain Core Soil Microbiota Stability While Driving Metabolic Decline and Network Evolution

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## ABSTRACT

Frequent drying-wetting cycles significantly affect soil microbial diversity and community structure, thereby mediating soil carbon cycling. Through three cycles of dry-wet experiments, this study combined continuous $CO_2$ monitoring, organic carbon spectroscopy, multi-omics analysis, single-cell Raman-$D_2O$ labeling, and microfluidic cultivation to demonstrate that repeated dry-wet alternations inhibit microbial metabolic activity and simplify interspecies interaction networks by reducing the proportion of labile carbon, while preserving the stability of the core soil microbial community. The results show that with increasing frequency of dry-wet cycles, cumulative soil $CO_2$ emissions and single-cell Raman CDR values exhibit a stepwise decrease, which is associated with a decline in labile carbon fractions and an increase in recalcitrant components. The microbial community displays high resilience (core taxa shared between DNA and RNA sequencing account for >70%), with cooperative interactions representing the dominant relationship pattern. DNA-based co-occurrence network parameters decreased with more frequent dry-wet cycles, whereas RNA-based network parameters first decreased and then increased, with positive correlations prevailing throughout. Raman-$D_2O$ labeling coupled with cultivation consistently identified Actinobacteria, Firmicutes, and Proteobacteria as the core functional microorganisms. This study reveals that repeated dry-wet stress enriches metabolically conservative taxa and reduces interaction complexity in response to the shift of organic carbon toward recalcitrant forms. By innovatively integrating multi-scale techniques, the research elucidates the synergistic mechanisms linking "microbes-substrates-functions," offering theoretical support for predicting soil microbial stability under climate change.

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# Widespread presence of extraordinary high-affinity of atmospheric methane oxidation by conventional methanotrophs in paddy soils across China

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**ABSTRACT**

Wetland systems are known methane ($CH_4$) sources. However, flooded rice fields are periodically drained. The paddy soils can absorb atmospheric $CH_4$ during the dry seasons due to high-affinity methane-oxidizing bacteria (methanotroph). Atmospheric $CH_4$ uptake can be induced during the low-affinity oxidation of high-concentration $CH_4$ in paddy soils. Multiple interacting factors control atmospheric $CH_4$ uptake in soil ecosystems. Broader biogeographical data are required to refine our understanding of the biotic and abiotic factors related to atmospheric $CH_4$ uptake in paddy soils. Thus, here, we aimed to assess the high-affinity $CH_4$ oxidation activity and explored the community composition of active atmospheric methanotrophs in nine geographically distinct Chinese paddy soils. Our findings demonstrated that high-affinity oxidation of 1.86 parts per million by volume (ppmv) $CH_4$ was quickly induced after 10,000 ppmv high-concentration $CH_4$ consumption by conventional methanotrophs. The ratios of 16S rRNA to rRNA genes (rDNA) for type II methanotrophs were higher than those for type I methanotrophs in all acid-neutral soils (excluding the alkaline soil) with high-affinity $CH_4$ oxidation activity. Both the 16S rRNA:rDNA ratios of type II methanotrophs and the abundance of $^{13}C$-labeled type II methanotrophs positively correlated with high-affinity $CH_4$ oxidation activity. Soil abiotic factors can regulate methanotrophic community composition and atmospheric $CH_4$ uptake in paddy soils. High-affinity methane oxidation activity, as well as the abundance of type II methanotroph, negatively correlated with soil pH, while they positively correlated with soil nutrient availability (soil organic carbon, total nitrogen, and ammonium-nitrogen). Our results indicate the importance of type II methanotrophs and abiotic factors in atmospheric $CH_4$ uptake in paddy soils. Our findings offer a broader biogeographical perspective on atmospheric $CH_4$ uptake in paddy soils. This provides evidence that periodically drained paddy fields can serve as the dry-season $CH_4$ sink. This study is anticipated to help in determining and devising greenhouse gas mitigation strategies through effective farm management in paddy fields.

# Decoding Deep Soil Microbial Response Dynamics to Afforestation in Semiarid Regions: Biotic-Abiotic Trade-offs Under Land-Use Transition

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**ABSTRACT**

Vegetation restoration is critical for improving the ecological environment and curbing land degradation. However, in semi-arid regions, long-term restoration projects have improved ecosystems at the expense of triggering persistent water deficits and substantial organic carbon loss in deep soils (>1 m). Critical knowledge gaps remain regarding how biotic (vegetation type, biomass) and abiotic factors (soil moisture, physicochemical properties) collectively regulate deep soil microbiomes under sustained restoration. We investigates bacterial and fungal community along vertical profile (0-500 cm depth) in abandoned grasslands (GL), shrublands (SL), and 20 and 40-year *Robinia pseudoacacia* plantations (RP20, RP40) on China's Loess Plateau. Our results showed that during the afforestation process, soil bacteria exhibited greater variability across soil layers, with bacterial abundance in the middle and deep layers decreasing by 9.95% and 8.40%, respectively, compared to the top layer. In contrast, fungi demonstrated stronger process heterogeneity. Fungal communities began to shift during the SL stage, showing opposing trends between the top-middle layers and the deep layer. Fungal communities in the top and middle layers reached lowest point in the SL before increasing, whereas those in the deep layers peaked at 86.58% in the SL and then decline. Afforestation exerted negative effects on deep-soil (300-500 cm) factors. Microbial communities adapted through a coordinated dual-path mechanism: exhibiting negative feedback to SWC ($\beta$ = -0.40,$\beta$ = -0.53) and positive feedback to TN ($\beta$ = 0.25) and SOC ($\beta$ = 0.67), which facilitated the enrichment of drought-tolerant taxa and the adaptation of functional groups. This synergistic response served as a key buffer against afforestation, guarding the stability of deep soil microbial communities. These results underscore the importance of incorporating vegetation and soil depth in future studies, with particular focus on deep soil ecosystems, to inform tailored restoration practices.

# Microbial growth is the key to soil organic carbon cycling

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**ABSTRACT**

The diverse microbial communities perform central roles in global biogeochemistry, yet only a small share of this diversity is actively growing. Microbial growth is a core life-history trait, virtually representing reliable performance of integrated physiological responses to environmental change. It is, however, unknown whether microbial growth rate and associated strategies differ fundamentally across biomes and environments, or how growth dictates the fate of assimilated carbon and soil organic carbon (SOC) accumulation and soil functions. Here, drawing on evidence from plot, regional and global scales in different biomes, we highlight the importance of microbial growth in driving SOC cycling and soil functions. We hypothesize that ecosystem-specific nature and environmental shifts decouple microbial growth from respiration by altering metabolism, function and viability, resulting an imbalance between carbon use efficiency (CUE) and SOC cycling, with profound consequences for carbon stocks in soil. Using long-term monitoring biodiversity platforms, we determined the ecology of soil microbial responses to above-belowground biodiversity changes, by quantifying microbial growth and functional traits. We explored how interactions between plant diversity, microbial communities, and soil properties impact carbon allocation toward growth, respiration, or extracellular enzyme production. Our findings reveal that realized growth rates manifest differently across biomes, for instance, higher maintenance respiration in alpine and polar regions results in lower CUE at low growth rates. Furthermore, regional observations indicate that the quantity of microbial-derived carbon depends more strongly on biomass size and total growth rates than on plant inputs or CUE. Specifically, belowground diversity and physiological traits drive a higher microbial contribution to SOC in temperate forests (dominated by K-strategists) than in temperate grasslands. Ultimately, we demonstrate that microbial growth is the primary 'volume control' for the microbial carbon pump, consequently, enhancing microbial growth is likely more effective than targeting CUE alone for soil carbon management. As such, microbial growth plays a core role in running global biogeochemistry and ecosystem functions.

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# Elucidating Soil Microbial Community Activity Through Sipros-and-Aerith-Assisted Proteomic and Metabolomic Stable Isotope Probing

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**ABSTRACT**

Understanding the activity of specific microorganisms within the complex soil ecosystem requires tools that can trace substrate metabolism into newly synthesized proteins and metabolites. To address this, we present an integrated approach using the upgraded Sipros algorithm for proteomic stable isotope probing (SIP) and the new Aerith package for isotopic visualization, designed to elucidate soil microbial community function.

Sipros[1] enables sensitive identification of $^{13}C$-labeled proteins and accurate quantification of their isotopic enrichment from soil samples. Benchmarked against other tools using labeled *E. coli* standards, Sipros demonstrated superior performance, offering more identifications with greater accuracy, especially at ≥5 atom% $^{13}C$, and a computational speed over 20 times faster than its predecessor. When applied to soil communities, Sipros successfully traced $^{13}C$ from labeled methanol and plant exudates to the active microbial populations assimilating them.

Complementing this quantitative analysis, the Aerith[2] R package allows for the simulation, visualization, and critical validation of isotopic patterns in labeled peptides and metabolites detected in SIP experiments. Aerith uses efficient algorithms to model isotopic distributions, providing a vital interface for researchers to manually inspect and confirm the spectral signatures of labeling within complex environmental samples.

Together, Sipros and Aerith form a powerful suite that enhances the resolution and reliability of SIP for soil microbial ecology. This combined approach—pairing high-throughput, sensitive protein-SIP analysis with robust tools for spectral visualization—provides a more complete framework for deciphering the metabolic activity that drives soil biogeochemical processes.

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# Microbial interactions drive microbial succession during soil formation

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**ABSTRACT**

Microbial communities underpin soil formation and ecosystem functioning, yet how microbial succession is initiated and progresses during soil formation remains poorly resolved. Soil development typically unfolds over decades to centuries, limiting direct observation of successional dynamics and the biotic mechanisms that drive them. In particular, it remains unclear whether and how changes in microbial interactions link soil-formation gradients to shifts in microbial diversity, community composition, and ecosystem functions under natural field conditions.

To address this gap, we combined a natural, continuous soil-formation gradient with dynamic inference of time-lagged, state-dependent microbial interactions to test whether interaction rewiring drives microbial succession. We leveraged a shrub-associated soil gradient in a desert region of China, where soil properties, plant inputs, and microbial communities vary smoothly from sandy soils to organic-matter-enriched soils under broadly similar climate, vegetation, and parent material. Spatial position along the gradient can therefore serve as an ordered proxy for successional progression.

Using this framework, quantitative amplicon sequencing revealed strong increases in bacterial and fungal abundance and richness toward more developed soils, accompanied by continuous compositional turnover along the gradient. Community composition shifted from stress-tolerant pioneer taxa to diverse heterotrophic and plant-associated taxa. Adaptive taxa identified from community ordination exhibited clear spatial partitioning into early-, mid-, and late-stage groups that differed in taxonomy, functional traits, and associations with roots and litter.

To link microbial succession to biotic interactions, we applied empirical dynamic modeling to infer state-dependent interactions while accounting for environmental variation. Microbial interaction networks became progressively denser along the gradient, and mean interaction strength per link showed a non-linear pattern consistent with compositional turnover. Importantly, interaction intensity aligned with successional position: taxa adaptive to a given stage exhibited the strongest interactions where they dominated in abundance, demonstrating a tight coupling between interaction networks and taxon dominance during succession.

These community-level changes coincided with enhanced soil functions. Soil carbon mineralization rates and enzymatic activities increased toward later stages, carbon limitation was progressively relaxed, and microbial functional efficiency increased during soil development.

Together, our results provide field-scale evidence that rewiring of microbial interaction networks drives microbial succession and functional transformation during soil formation. This study highlights microbial interactions as a key, dynamic mechanism underlying soil ecosystem development and offers new insights for managing soil functional trajectories.

# Soil Bacterial Diversity at the Molecular Level: Origins, Consequences, and Implications

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**ABSTRACT**

A central challenge in contemporary microbiology is to bridge the gap between molecular mechanisms operating at the cellular level and population-level behaviors that emerge under complex environments such as soils. A key task in this endeavor is to elucidate the evolutionary significance of the vast number of genetic mutants that arise in nature. Understanding the environmental conditions under which such mutants emerge, as well as their subsequent evolutionary fate, is essential for correctly interpreting the biological and ecological functions of the corresponding genes. We will integrate recent findings from our laboratory to explore the origins, functional consequences, and evolutionary implications of spontaneous mutations in genes involved in siderophore biosynthesis and histidine catabolism. Using *Pseudomonas fluorescens* as a model system, and combining experimental evolution, genomics, and molecular genetics, we dissect genotype–phenotype–environment interactions at the molecular, individual, and population levels.

Siderophore (pyoverdine, Pvd) secretion by *Pseudomonas* species represents a major model system for studying microbial cooperation. Because extracellular siderophores can be taken up by neighboring cells, they are considered public goods, with producing cells viewed as cooperators and non-producing cells as cheaters. However, through analyses of spontaneous siderophore-deficient mutants arising during experimental evolution under well-defined laboratory conditions, we demonstrate that the regulatory architecture of the wild-type strain is maladaptive for growth in closed environments. Consequently, cooperation and cheating alone are insufficient to explain the emergence of siderophore non-producing mutants.

In addition, with the widespread application of genome sequencing, environmental isolates (wild-type strains) are frequently found to harbor mutations in key metabolic genes encoding degradative enzymes, raising questions about their adaptive capacity. A representative example is the histidine utilization pathway in the plant pathogen *Pseudomonas syringae*, where mutations—including nonsense mutations in *hut* genes for histidine utilization—are commonly observed. We will discuss the evolutionary routes and environmental conditions under which mutants may regain the ability to utilize histidine.

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# Synergistic remediation of desertification and carbon sequestration in extreme environments via region-tailored acclimated microbial-biochar systems

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**ABSTRACT**

Synergistic remediation of desertification and carbon sequestration in extreme environments remains poorly understood, especially under low-temperature and drought constraints. To fill this gap, we isolated three indigenous functional microbial strains (assigned No. 56, 86, 111) from the Loess Plateau and Mu Us Sandy Land, and acclimated them to the distinct extreme environments of three target desertified regions (Zhongwei, Jingbian, Mangya): Strain 56 (highly drought- and temperature-difference-tolerant phosphorus-solubilizing microorganisms, PBSMs) for Zhongwei; Strain 86 (mild saline-alkali-tolerant *Chitinophaga lutea*) for Jingbian; and Strain 111 (cold-tolerant *Pseudomonas mandelii* CBs-1, synthesizing poly-β-hydroxybutyrate, PHB, to adapt to low-temperature arid conditions) for Mangya. Five experimental treatments with three replicates were set for in-situ field trials (commencing in November 2025 across the three extreme environments): blank control (CK), three single-strain treatments (Strain 56 alone, Strain 86 alone, Strain 111 alone), and one core treatment (mixed culture of the three strains + biochar). The results showed that Zhongwei desert formed stable biological crusts within 1 month, with >30% higher water retention and 25% higher survival of native *Artemisia ordosica* and *Hippophae rhamnoides*; Jingbian observed 60% inhibition of *Fusarium*, 15% lower salinization, and 40% higher vegetation growth; Mangya desert maintained >80% *Pseudomonas mandelii* survival (-5~25℃) with 6-month sand fixation and 35% higher cold-tolerant vegetation survival. All regions showed improved microbial diversity and stable microecosystems. Notably, the formation of biological crusts and stable microecosystems also lays a solid foundation for enhancing soil carbon sequestration potential in desertified areas. The technology is scalable, eco-friendly (no chemical residues), and cost-controllable (local raw material rate >90%). Our findings verify the adaptability and effectiveness of this region-specific microbial technology. Future efforts will optimize microbial community ratios and carrier functions, realize intelligent screening via machine learning, and promote application in more desertified regions, providing solid support for northwest China's desertification control and ecological security barrier construction.

**Key words:** Region-tailored microbial-biochar system, Desertification remediation, Carbon sequestration, Extreme environment adaptation, Indigenous functional microorganism

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# Microbial CHON Assimilation and Stoichiometric Strategies in Natural and Agricultural Black Soils Revealed by Multi-Isotope Tracing

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**ABSTRACT**

Intensive agricultural practices can profoundly reshape soil microbial activity and ecosystem functioning, yet their impacts on microbial elemental coupling across carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) remain poorly quantified. How long-term land use influences microbial CHON assimilation strategies is still unclear. Here, we applied a multi-isotope tracing approach to compare microbial metabolic activity and stoichiometry between natural and agricultural black soils.

Soils were incubated under controlled laboratory conditions with a factorial design combining water tracers ($^2H_2O$ or $H_2{}^{18}O$) and substrate additions ($^{13}$C-glucose and $^{15}$N-$NH_4Cl$). Treatments included water-only controls, single-element labeling, and combined C–N labeling, allowing simultaneous quantification of microbial growth, substrate assimilation, and elemental coupling. Incorporation of $^{13}$C, $^2$H, $^{18}$O, and $^{15}$N into soil organic matter was determined as atom percent excess, and net CHON incorporation was used to calculate microbial stoichiometric ratios. Soil $CO_2$ production was measured to assess respiratory responses, and microbial community dynamics were further evaluated using DNA and RNA-based sequencing.

Glucose addition markedly stimulated microbial $^{13}$C incorporation and $CO_2$ emission in both soils, whereas water-only treatments showed minimal isotopic enrichment. Agricultural soils exhibited higher C assimilation and respiration rates than natural soils, indicating a more rapid metabolic response to labile substrates. In contrast, natural soils showed lower C incorporation but more constrained CHON stoichiometric shifts. Combined C and N additions further altered elemental coupling, resulting in distinct C:N, C:H, and C:O ratios between soil types.

Our results demonstrate that long-term agricultural management alters microbial CHON assimilation strategies by promoting rapid carbon uptake and respiratory activity at the expense of balanced elemental allocation. This study highlights the value of multi-element isotope approaches for linking microbial metabolism, stoichiometry, and soil resilience under intensive land use.

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# Multi-stressor environments reshape soil microbial biodiversity and genomic strategies, favoring stress-adapted and unknown taxa

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**ABSTRACT**

Soil microorganisms constitute the largest portion of Earth's biodiversity, yet their responses to multiple concurrent environmental stressors remain poorly resolved at large spatial scales. Through an extensive cross-ecosystem field survey, we examined how the number of environmental stressors exceeding relevant stressor thresholds shapes soil microbial community structure, genomic traits, and ecological strategies. We show that as the number of high stressors increases, the diversity and abundance of rare microbial taxa decline. In contrast, unknown taxa and genes become progressively enriched. Metagenome-assembled genomes from common taxa reveal exhibit resistance or positive responsiveness to multiple stressors. These resistant common taxa display reduced genomic potential for core cellular processes but enhanced capabilities for environmental sensing, genetic regulation, and metabolic versatility. Furthermore, the number of stressors, more than their average intensity, was the dominant predictor of shifts in microbial traits linked to growth inhibition and stress adaptation. Our findings demonstrate that multi-stressor environments drive soil microbial communities toward increasingly unknown and stress-adapted lineages while diminishing rare biodiversity, with implications for ecosystem functioning under global change.

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# Summer drought impacts micropredator abundance and microbial foodweb structure in a rewetted fen peatland

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**ABSTRACT**

Summer drought significantly affects soil microbiome diversity and functioning, and metabolic interactions in wetland ecosystems. However, drought effects on the microbial food web in wetlands is much less understood.

We investigated the dynamics of bacterivorous microorganisms and prey bacteria (PBac) in a rewetted fen peatland before, during and after summer drought, using 16S rRNA and 18S rRNA gene amplicon sequencing and quantitative metatranscriptomics. Based on SSU rRNA transcripts and genes, we screened for bacterivores including bacterivorous bacteria (BBac), protists (BPro), and nematodes (BNem), as well as those with a host-dependent lifestyle including Ca. *Patescibacteria* and DPANN archaea (PD). In addition, bacteriophage transcripts were enumerated.

The summer drought led to a higher diversity of BPro and BBac in the fen as compared to pre-drought months and was accompanied by decrease in water levels and an increase in redox potential. The SSU rRNA transcripts abundances for all bacterivores (with the exception of PD) increased during drought, reaching a peak in October. Notably, the transcript abundance of all bacterivores remained above the pre-drought level after the end of drought, suggesting a long-lasting impact of summer drought on bacterivore dynamics. This became more evident when assessing the bacterivore-to-prey bacteria ratios, with the ratios of BBac-, BPro-, and BNem-to-PBac increasing by more than two-fold compared to the pre-drought ratio.

This study provides a holistic view of diversity and composition of bacterivores in a fen soil microbiomes, including PD and bacteriophages, and revealed a long-lasting impact of summer drought on bacterivore and food web dynamics. The strong responses of these bacterivores may lead to changes in ecosystem functioning through modulated trophic interactions in a changing climate.

# Effects of Disturbance Intensity on Soil Microbial Diversity, Composition, and Network Complexity in Coastal Georgia, USA

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**ABSTRACT**

Soil microbial diversity and community composition are strongly influenced by anthropogenic activities and environmental conditions, which in turn regulate ecosystem functions. Disturbance intensity often reshapes microbial community structure and co-occurrence networks, thereby affecting ecosystem resilience and functionality. In this study, we investigated the diversity, community composition, and network complexity of soil bacterial, fungal, and eukaryotic (including fungal) communities across a disturbance gradient encompassing cropland, transition, and forest soils at three locations in the coastal region of Georgia, USA. Illumina high-throughput DNA sequencing targeting the 16S rRNA (Klindworth *et al.*, 2013, bacteria), ITS region (White *et al.*, 1990, fungi only), and 18S rRNA (Stoeck *et al.*, 2010, eukaryotes including fungi, same as below) genes was used to characterize microbial communities and their co-occurrence networks. Our results indicated that soil bacterial community structures differed significantly among disturbance intensities ($p = 0.01$) but not among locations ($p = 0.09$), suggesting that bacterial taxa are more widely distributed at the local scale. In contrast, fungal and eukaryotic community structures varied significantly both across disturbance intensities ($p = 0.02$ for fungi, and $p = 0.01$ for eukaryotes) as well as three different locations ($p = 0.01$ for fungi, and $p = 0.03$ for eukaryotes), indicating more localized or endemic distributions. Network analysis revealed that bacterial network complexity declined with increasing disturbance intensity, as shown by a reduction in node connectivity (degree) from 890 in forest soils to 593 in cropland soils. Compared with less-disturbed forest soils, agricultural practices significantly decreased soil bacterial richness and Shannon diversity. Whereas the network complexity of fungi and other eukaryotes remained relatively stable across increasing disturbance intensities. The richness and Shannon diversity of soil fungi and other eukaryotes were significantly higher in forest soils than in crop soils. Soil microbial communities are strongly shaped by disturbance intensity. Proteobacteria dominate in highly disturbed crop soils, whereas transitional and forest soils have lower abundances. Forest soils are enriched in Basidiomycota fungi, while Tubulinea, a major grouping of Amoebozoa, are most abundant in crop soils and least abundant in forest soils. The important role of Tubulinea in predating soil bacteria may be closely linked to the lower bacterial diversity and diminished network complexity observed in crop soils. Overall, these findings indicate that varying disturbance intensities substantially alter soil microbial diversity, community composition, and co-occurrence network complexity, potentially affecting ecosystem stability and resilience in coastal soils of Georgia, USA.

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# The Effect of Nitrogen Enrichment on Soil Fungal and Bacterial Community Assembly Processes and Phylogenetic Diversity in Wetland

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**ABSTRACT**

Soil microorganisms are vital components of wetland ecosystems, and their responses to long-term remain nitrogen (N) enrichment remains unclear. To investigate their evolutionary trajectory during sustained N enrichment, a synergistic treatment combining N input with vegetation removal for 11 years (CK: 0 g N $m^{-2}$ $yr^{-1}$; N1: 6 g N $m^{-2}$ $yr^{-1}$; N2: 12 g N $m^{-2}$ $yr^{-1}$; N3: 24 g N $m^{-2}$ $yr^{-1}$; CKW: vegetation removal treatment; N3W: 24 g N $m^{-2}$ $yr^{-1}$ and vegetation removal treatment). The microbial community traits were analyzed using 16S rRNA and ITS sequencing technologies. The results showed that both soil fungal and bacterial communities significantly increased deterministic processes under both low N input (N1) and high N input with vegetation removal (N3W) treatments. Deterministic processes dominated in fungal communities under both treatments, deterministic processes in bacterial communities only emerged under both treatments.This not only indicates that fungal communities are more strongly influenced by environmental factors, but also demonstrates that deterministic processes are enhanced under both scenarios: low nitrogen input alone and high nitrogen input with vegetation removal. Mantel tests revealed that the increase in deterministic processes was significantly positively correlated with soil TN content, while fungi exhibited a significant positive correlation with soil MBC content. Compared to community assembly processes, soil microbial phylogenetic diversity exhibited lesser susceptibility to N input. Both fungal and bacterial phylogenetic α-diversity showed no significant changes under N input treatments, with significant alterations occurring under the synergistic effect of vegetation removal and high N input when compared with the CKW treatment. Under the N3W treatment, fungal phylogenetic α-diversity increased significantly, while bacterial diversity decreased. Correlation analysis revealed that fungal phylogenetic α-diversity positively correlated with soil $NO_3^-$-N and C:N ratios, but negatively correlated with soil pH, TP, and MBC; bacterial diversity was positively correlated with soil pH and MBC, but negatively correlated with soil $NH_4^+$-N and $NO_3^-$-N. Moreover, microbial phylogenetic β-diversity followed the same trend as α-diversity. Fungal phylogenetic β-diversity were primarily influenced by $NH_4^+$-N, pH, and C:P ratios, whereas bacterial phylogenetic β-diversity were mainly affected by soil MBC and pH. This study elucidates the distinct community assembly mechanisms and phylogenetic diversity patterns of fungal and bacterial communities in wetland soils under N enrichment, providing theoretical framework for predicting microbial evolutionary mechanisms in N enrichment wetland ecosystems.

**KEY WORDS:** Nitrogen input, Microbial communities, Stochastic and deterministic processes, Phylogenetic diversity

# Clays as Therapeutic Agents: A Focus on Mineralogy and Geochemistry of Geophagic Clays at Mfensi-Adankwame in the Ashanti Region of Ghana and their Healing Properties

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**ABSTRACT**

To determine the scientific understanding of both mineralogy and geochemistry, in addition to establishing the pH values of healing clays, twenty (20) clay-like materials, which are believed to be used as therapeutic agents for treating various ailments, were procured. The samples were sourced from in situ field materials, stockpile materials brought up from 4 metres below ground level for processing, and finished clay products that originated from the study area and are sold in markets. All 20 samples, each weighing 100 grams, were sent to the ALS geochemical laboratory for multi-elemental analysis using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). X-ray Diffraction (XRD) technique was used on four in situ clay materials to analyze the mineralogical composition. To establish the pH and EC values of the healing clays, 8 clay materials from different locations, each weighing 10 grams, were analyzed using JENWAY 350 pH meter and Hanna Instrument, respectively. The findings from the XRD Qualitative Analytical technique identified Quartz, Muscovite and Kaolinite as the predominant minerals in the analyzed clay samples. Rutile and Anatase were also revealed in some of the samples, although in trace amounts. The pH values of all samples ranged from 7.43 to 8.60, indicating an alkaline environment. The EC values of the clay samples fell below 2.0 dS/m, indicating non-saline conditions according to FAO guidelines, and are far lower than the threshold for saline materials (≥4 dS/m). From the geochemical analysis, most of the elements found in the clay sampled media showed depletion of macro, micro and toxic elements, which can be attributed to their low EC values. The implication is that the clay consumed by the practitioners would be harmless, as it lacks deleterious constituents and possesses alkaline properties that neutralize the acidic conditions within the stomach. It is evident that ingesting clay to alleviate stomach discomfort caused by excessive acid secretion that causes heartburn or ulcers seems to be justifiable because of the alkaline nature of the sampled clays. However, caution should be exercised when considering its use as a wholesale product due to potential variations in mineralogy and associated narratives. To add to this, the abundance of quartz in the clay samples poses a potential threat to human dental enamel upon ingestion. Thus, it is imperative that mineralogical and geochemical analyses be conducted prior to the consumption of clay as a medicinal product.

**Keywords:** mineralogy, geochemistry, therapeutic agent, healing clays, stomach discomfort

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# The mineralogical mechanisms of solid phase aluminum mobilization during soil acidification

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## ABSTRACT

The toxic effect of active aluminum (Al) on crops is a primary manifestation of soil acidification damage. During soil acidification, exchangeable $H^+$ is transformed into exchangeable $Al^{3+}$, though the detailed mechanism remains unclear. This study investigated the mobilization of Al during soil acidification, focusing on the roles of surface hydroxyl groups and the Al coordination environment in phyllosilicate minerals and acid dryland soils. Traditional electrochemical methods were combined with modern spectroscopic techniques to elucidate the underlying mechanisms. Surface hydroxyl groups of montmorillonite were removed by high-temperature treatment (Fig. 1). After high-temperature treatment, dehydroxylation reduced mineral crystallinity, layer spacing, pH, and cation exchange capacity (CEC). Al mobilization experiments at constant pH, conducted using an automatic potentiometric titrator, revealed that the removal of surface hydroxyl groups inhibited Al mobilization, with the inhibitory effect strengthening as treatment temperature increased up to the complete dehydroxylation point (Fig. 2). This indicated that protonation of surface hydroxyl groups played a critical role in releasing mineral solid phase Al. Furthermore, four phyllosilicate minerals with differing Al coordination nature were studied. $^{27}Al$ magic-angle spinning solid-state nuclear magnetic resonance (MAS-NMR) spectra showed kaolinite contained only octahedral Al ($Al^{VI}$), phlogopite and illite contained only tetrahedral Al ($Al^{IV}$), and vermiculite contained both. At pH < 5.1, the amount of Al released followed the order: illite > vermiculite > phlogopite > kaolinite, correlating with the CEC and tetrahedral Al content of the minerals. Al mobilization kinetics at constant pH, well-described by the Elovich equation, showed the release rate was generally higher in minerals containing $Al^{IV}$ (e.g., illite, phlogopite) than in kaolinite (only $Al^{VI}$), and increased with decreasing pH. The experimental results of vermiculite acidification with different HCl concentrations showed that the intensity of the $Al^{IV}$ peak in the $^{27}Al$ MAS-NMR spectra gradually decreased, while the intensity of the $Al^{VI}$ peak gradually increased with rising HCl concentration (Fig. 3). This further demonstrated that $Al^{IV}$ was more readily mobilized than $Al^{VI}$. These findings were corroborated by studies on two Oxisols at different ages and four zonal soils. The 10-kilo-annum Oxisol, which contained detectable $Al^{IV}$, released more Al during acidification than the 1330-kilo-annum Oxisol, which contained only $Al^{VI}$. The Al release amount across zonal soils was consistent with their relative $Al^{IV}$ content. This confirmed that $Al^{IV}$ was more readily mobilized than $Al^{VI}$ during soil acidification.

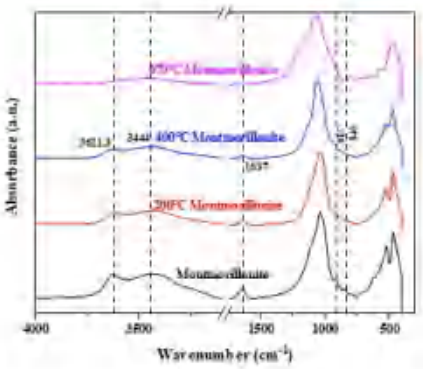



Fig. 1 Fourier transform infrared spectra of montmorillonite as well as the mineral treated at different temperatures.

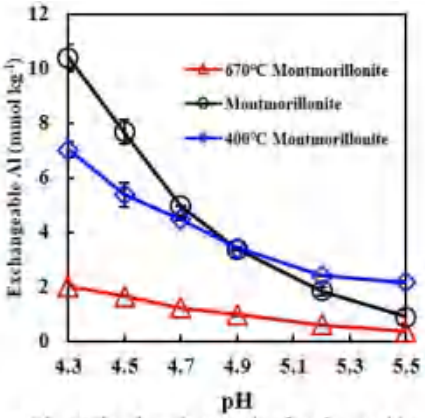



Fig. 2 The changing trends of exchangeable Al with pH during the acidification of montmorillonite.

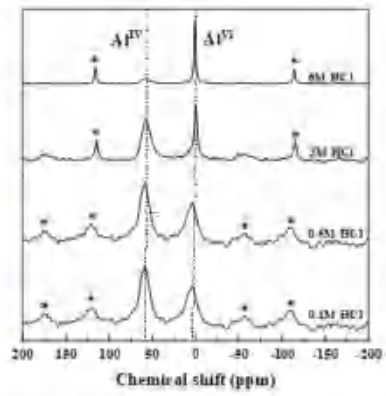



Fig. 3 $^{27}Al$ MAS-NMR spectra of vermiculite treated with different concentrations of HCl for 24 h. The symbol * represents rotating sideband.

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# Quantifying the direct and indirect effects of soil-forming factors on clay mineral abundance

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## ABSTRACT

Secondary clay minerals play crucial roles in controlling soil physicochemical properties, and their abundances are governed by the soil-forming factors, especially parent material, climate, and time. Despite studies on single drivers of secondary mineral abundances, cross-regional, multifactor analyses are lacking, partly due to their highly complex interactions. We propose that soil solution properties (e.g., pH and $H_4SiO_4$ activity) and weathering indices (e.g., total reserve base, TRB), which reflect the influence of parent material, climate and time, could link these factors with secondary minerals and be effectively used to predict their abundances.

We identified key variables for predicting mineral abundances, including kaolinite, gibbsite, vermiculite+mica, and acid ammonium oxalate extractable Si ($Si_o$; a proxy for allophane and imogolite) using regression Random Forest (RF) and correlation analyses. Then, based on the identified variable set, we tested a hypothesized model using structural equation modeling (SEM). The model incorporated both direct effects from soil-forming factors and indirect pathways. The primary indirect pathway was modeled as a hierarchical cascade: Climate/Parent Material (Layer 1) → Weathering Indices (Layer 2) → Soil Solution Properties (Layer 3) → Secondary Mineral Abundance (Layer 4). The analysis used subsurface soil samples (mostly 30–60 cm depth) from 213 sites covering temperatures of 7.0–26.9°C, precipitation of 720–4301 mm, and parent materials encompassing igneous and sedimentary rocks. Predictor variables representing soil-forming factors included the following: mean annual temperature (MAT), precipitation (MAP), and excess precipitation (EP) as climatic factors; $Al_2O_3$ + $Fe_2O_3$ and parent material type (binary: sedimentary = 1, igneous = 0) as parent material factors; slope and aspect as topographic factors; and total and aboveground potential net primary productivity (TNPP, ANPP) as biological factors. Although weathering indices are influenced by parent material, they were considered proxy variables reflecting the time factor.

After examining multicollinearity and performing variable selection via RF and correlation analyses, variables showing strong influence (e.g., correlation coefficient > 0.3) were selected for SEM: for kaolinite and gibbsite, MAT, parent material type, TRB, and $H_4SiO_4$ activity; and for vermiculite+mica and $Si_o$, MAT, EP, parent material type, TRB, and pH. The $R^2$ values ($p < 0.05$) for the generated models were 0.48 (kaolinite), 0.32 (gibbsite), 0.61 (vermiculite+mica), and 0.47 ($Si_o$). In all models, the dominant indirect effects via soil solution properties or weathering indices were substantial, accounting for 34–100% of the total effect. Collectively, pH, TRB, and $H_4SiO_4$ activity capture the key pathways connecting soil-forming factors to secondary mineral abundances.

# Models of rock weathering in soil environments based on rock fractal geometry

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**ABSTRACT**

The aim of the present research is the study of the solid rock weathering and following transformation into clayey material in the soil environments. The objects are represented by the shallow and mature soils that are derived from and underlain by the highly sensitive to weathering rocks (ultramafic and mafic). The studied soils have formed in the cold environments of the Polar Urals and the Central Siberian Plateau. The mineralogical compositions of rocks and soils were determined on randomly oriented powder specimens and textured specimens of the soil fine size fractions using XRD. The thin sections of rock fragments from the soils were studied by optical microscopy. The specific surface area and the pore size distribution in the rock fragments were determined by low-temperature nitrogen adsorption. The mesostructure data (structural parameters in the range 2–100 nm) and fractal properties of the rocks were investigated by the small angle neutron scattering (SANS) method.

Based on SANS data the ultramafic rock can be seen as a mass fractal structure. The fractal nature of the rock helps to explain the fact that rock transformation into clayey material occurs throughout all sample volume. That leads to appearance of smectite, which was not identified in the rock itself, in the soil profile of Haplic Cryosols (Reductaquic). The rock weathering is fast enough to retain a sufficient amount of smectite, due to continuous supply of new portions of this unstable in the soil horizons mineral.

The studied mafic rock can be imagined as a surface fractal structure that means the phase boundary (hard rock / pore space) is characterized by fractal structure. The rock fragments from the bottom to the upper horizons became more dispersed but smoother. In the fine earth smectite conserves in the inherited aggregates, in which this unstable mineral is protected against dissolution in acidic Entic Podzols.

Thus, two models of the solid rock weathering and transformation into clayey material in the soil environments were shown based on the fractal nature of the studied rocks. That reveals the key role of nanoscale processes based on soil mineralogy in understanding the macro level of rock weathering and pedogenesis.

**Acknowledgments**

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# Clay mineralogy of soils from cold environments of Siberia, Russia

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**ABSTRACT**

The aim of this research is the study of clay mineralogy of the soils formed under cold continental climate in a broad landscape range of (i) the Kolyma Lowland (the Alazeya River Basin): coastal marsh (Gleyic Tidalic Fluvisols), alas meadows on the plain composed of the ice complex deposits (Stagnic Gleysols), and typical northern taiga (Histic Cryosols; (ii) middle taiga in the Central Yakutian Plain (Cambic Cryosols); (iii) middle taiga in the Lena (Prilenskoe) Plateau (Entic Podzols and Cryosols); and (iv) southern taiga in the Lena–Angara Plateau (Calcaric Chromic or Calcaric Rhodic Luvisols and Calcaric Albic Rhodic Luvisols). The mineralogical compositions of rocks and soils were determined on textured specimens of the soil fine size (<0.001 mm) fractions using XRD. The thin sections of soils were studied by ADF U300-P polarizing microscope (Chaina) in plane-polarized light (PPL), cross-polarized light (XPL).

Based on findings of XRD data the soil mineral associations and mineral phase distribution in the soils profiles are affected by inheritance of minerals from the parent substrates and their sensitivity to weathering in acidic environment. The soils of the Alazeya River Basin are characterized by occurrence of (i) vermiculite in the acidic soil horizons of the alas meadow and zonal northern taiga landscapes and (ii) iron hydroxide (lepidocrocite) in the profile of the marsh meadow soils as a result of pedogenesis. Cambic Cryosols (pale soil) of the Central Yakutian Plain are weakly differentiated, their mineral association inherited from loesslike loams differ from that of European Russia due to higher proportion of chlorite.

Despite differences in the particle-size distribution and mineralogical composition, the studied soils formed on the eluvium of Mesozoic noncalcareous sediments of the Lena Plateau are characterized by the high proportion of kaolinite among clay minerals. The illite–chlorite association of clay minerals with a predominance of dioctahedral minerals occurs in the soils on the red colored calcareous Cambrian substrate of the Lena-Angara Plateau. These soils are characterized by the vertical homogeneity of the parent material that was confirmed by the same Coarse/Fine related distribution and similar shape of large grains in thin sections of soil. Micromorphological studies of soils have shown occurrence of the texturally differentiated pedofeatures in the most humid conditions that increase along with higher altitudes. At lower altitudes, the signs of clay illuviation are less pronounced, though they can be traced in the profiles.

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# Contributions to the Study of Geophagic Clays in Africa

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**ABSTRACT**

Geophagia is the deliberate ingestion of clayey soils and materials; the subject is very wide, multi-, trans-, and inter-disciplined. It is a practice that may likely persist and so making geophagic clays safer for human ingestion has been one of the goals behind its research. The scope of this presentation is limited to the characterisation of geophagic clays from selected countries in Africa including Botswana, Cameroon, Democratic Republic of Congo, Eswatini, Nigeria, and South Africa. Questionnaires were administered to geophagists (individuals who practice geophagia) to understand the types of geophagic clayey materials consumed. The characterisation of the geophagic materials concentrated on their physicochemical and chemical properties and understanding the relationship between the postulated reasons for ingestion of the geophagic clays and these properties. Studies on the mineralogical and chemical compositions of geophagic clays from different regions of South Africa, and different countries indicate huge variations in the properties of the clays ingested as shown in Ekosse and Ngole (2012), Ekosse et. al., (2011), and Ngole and Ekosse (2012), Variations in geophagic materials were also identified and discussed appropriately with specific References to geophagic clays from different countries (Ngole-Jeme and Ekosse, 2015). Though geophagic clays could be sources of nutrient supplement (Ngole and Ekosse (2012), they could have loads of geohelminths which could lead to human geohelminth infection (Sumbele et. al., 2013).

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# Mineralogical and Geochemical Contributions to the Study of Clays and Clay Minerals in Africa

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**ABSTRACT**

Africa is endowed with vast deposits and occurrences of both primary and secondary Clays and Clay Minerals of which their geochemical and mineralogical properties are related to their geneses. Clays and Clay Minerals are widely used in many conventional, traditional and emerging applications; and do contribute to national economies in the continent. Of major economic importance is kaolin that find usage in many applications due to influences from its geochemical and mineralogical compositions and properties. With increasing continental population in Africa, demands for food security, augmented industrialization, improved urbanization, and technological advancement hinging on the Fourth Industrial Revolution (4IR) will continue to be on the rise. There is thus the need for better exploration and exploitation of known and unknown Clays and Clay Mineral Resources of the continent for the benefit of its inhabitants. This presentation, which focuses on mineralogy and geochemistry, is part of research efforts conducted on Clays and Clay Minerals in five countries in Africa over the last twenty-five years by the author. Studies covered mainly kaolin, and to a lesser extent talc, illite, and smectite. The kaolin deposits could be primary (hydrothermal, residual or mixed hydrothermal and residual) or secondary (Ekosse, 2010); and kaolinite formed by mineral alteration of feldspar and muscovite contained in rocks such as granite and rhyolite as indicated in equations 1 and 2.

$2KAl_3Si_3O_{10}(OH)_2 + 2H^+ + 3H_2O = 3Al_2Si2O_5(OH)_4 + 2K^+$ (1)

$2AlSi_3O_8 + 2H^+ = 9H_2O = Al_2Si_2O_5(OH)_4 + 2K^+ + 4H_4SiO_4$ (2)

Extensive fieldwork covering Botswana, Cameroon, Eswatini, Gabon, Ghana, Nigeria, and South Africa was conducted by visiting selected formations, deposits, and occurrences that had argillaceous rocks and sediments, and studying soils next to abandoned manganese mine, human settlements and clayey materials from volcanic cones. X-ray powder diffraction analysis was employed for the identification and characterization of mineral phases present in the samples. Flame photometry, X-ray Fluorescence Spectrometry, Laser Ablation – Inductively Coupled Plasma – Mass Spectrometry, Fourier Transform Infrared Spectrophotometry, Thermogravimetric Analysis and Differential Scanning Calorimetry analytical techniques were applied in mineralogically and chemically characterizing the samples. The research findings, published in different scientific outlets, are discussed from an integrated perspective.

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# Elucidation of Chemical Structure of Soil Clay Minerals Using Electron Probe Microanalyzer

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## ABSTRACT

The stability of soil clay minerals in the soil environment remains unclear. The present study aims to elucidate chemical structural information of soil clay minerals including isomorphic substitution and detect weathering-induced structural changes of them in a soil profile. For the purpose, the authors investigated the clay minerals at a single-particle level using electron probe microanalyzer (EPMA).

To validate the accuracy of the EPMA method, six standard clays obtained from the Clay Science Society of Japan (Miyawaki et al., 2010) were investigated. These standard clays were analyzed untreated and after Cs-saturation treatment. For detecting structural changes due to weathering, soil clay fractions (< 2 μm) were separated from soil samples collected from A, Bw1, Bw2, BC, and C horizons from a Cambisol (Inceptisol) profile in Fukuoka, Japan (Mori et al., 2023). The soil clay fractions were subjected to dithionite-citrate-bicarbonate treatment, hot citrate treatment, and Cs-saturation treatments, sequentially. Those clay samples were embedded in epoxy resin, polished, carbon-coated, and analyzed with EPMA (JEOL JXA-8530F). The chemical formulas were normalized based on the information of mineral species identified by powder X-ray diffraction analysis (Mori et al., 2023). Non-exchangeable K was defined as K remained after the Cs-saturation treatment.

The analysis of standard clays revealed that the EPMA method successfully collected target mineral data from impure samples, yielding accurate structural information. In the analysis of soil clays, it was clarified that beidellite was the predominant clay mineral with an averaged chemical formula of $[K_{0.35}, Na_{0.06}, Ca_{0.03}, Mg_{0.06} (Si_{3.67}, Al_{0.33})(Al_{1.65}, Fe^{III}_{0.01}, Fe^{II}_{0.22}, Mg_{0.08}, Ti_{0.04}) O_{10}(OH)_2]$. Although the soil profile has developed horizons with soil formation, the chemical structure of the beidellite showed no statistically significant differences in the frequency and type of isomorphic substitution among horizons, remaining constant throughout the soil profile. Furthermore, non-exchangeable K accounted for approximately 25% of the total interlayer charge, and this value was also consistent across all horizons. These results suggest that beidellite is highly stable in the acidic weathering environment, and that isomorphic substitution within its tetrahedral sheet leads to strong interlayer fixation of K, similar to illite. Further research is needed to elucidate the structural changes in clay minerals during weathering and enhance our understanding of weathering processes.

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# Crystallinity–solubility relationship of phytoliths derived from different gramineous plants: validation using X-ray diffraction analysis

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**ABSTRACT**

Silicon (Si), a beneficial element for gramineous plants, is the second most abundant element in soils. Plant available Si in soil primarily originates from soil minerals, however, phytoliths, plant-derived hydrated amorphous silica, have recently attracted attention as an important alternative source of available Si. The solubility of phytoliths varies among plant species; but the underlying factors governing this variability remain unclear even though it directly affects the Si-supplying potential. Therefore, based on the hypothesis that differences in crystallinity determine phytolith solubility, we investigated phytoliths extracted from different species and organs of gramineous plants to clarify the physicochemical factors determining their solubility.

Phytoliths were prepared from the culms, branches, and leaves of moso bamboo (*Phyllostachys pubescens*), the straw and husks of rice (*Oryza sativa*) and the stems and leaves of sugarcane (*Saccharum officinarum*) using a wet digestion method. The crystallinity of the prepared phytoliths was evaluated using the References intensity ratio (RIR) method based on X-ray diffraction (XRD) analysis. The phytolith (200 mg) was mixed with 50 mg of corundum ($\alpha$-$Al_2O_3$) as an internal standard for RIR measurements. Also, amorphous silica and sea sand were used as external $SiO_2$ standards representing 100% opal-A and $\alpha$-quartz, respectively. The opal-A phase (i.e., amorphousness) and $\alpha$-$SiO_2$ phase (i.e., crystallinity) were calculated from the ratios of the RIRs of the phytolith opal-A peak ($2\theta = 22.1°$) and $\alpha$-quartz peak ($2\theta = 26.6°$) to that of amorphous silica and sea sand, respectively. The solubilities of the phytoliths and the external $SiO_2$ standards were determined via 0.2-M NaOH extraction.

The contents of the opal-A and $\alpha$-quartz phases in the phytoliths were on average 85.3% and 4.8%, respectively across different organs and species, with a negative correlation ($p < 0.01$). The opal-A phase increased from the proximal to distal parts of the plants. The initial Si dissolution rate and maximum Si dissolution amount of the phytoliths were on average 138 g Si $kg^{-1}$ $h^{-1}$ and 343 g Si $kg^{-1}$, respectively. Both parameters exhibited an increasing trend from the proximal to distal parts. The initial dissolution rate exhibited a positive correlation with the opal-A phase ($p < 0.01$), whereas the maximum dissolution amount exhibited a negative correlation with the $\alpha$-quartz phase ($p < 0.01$) (Fig. 1). These results indicate that differences in tissue developmental stage across plant organs control phytolith crystallinity, i.e., the relative abundance of opal-A and $\alpha$-quartz. This composition, in turn, strongly controls phytolith solubility, specifically the dissolution rate and capacity, respectively. In conclusion, these findings quantitatively elucidate the mechanism controlling Si supply from phytolith, thereby enabling a more precise estimation of Si supply from gramineous plant based on developmental stage.

**Keywords:** crystallinity, *Gramineae*, phytolith, Si solubility, X-ray diffraction

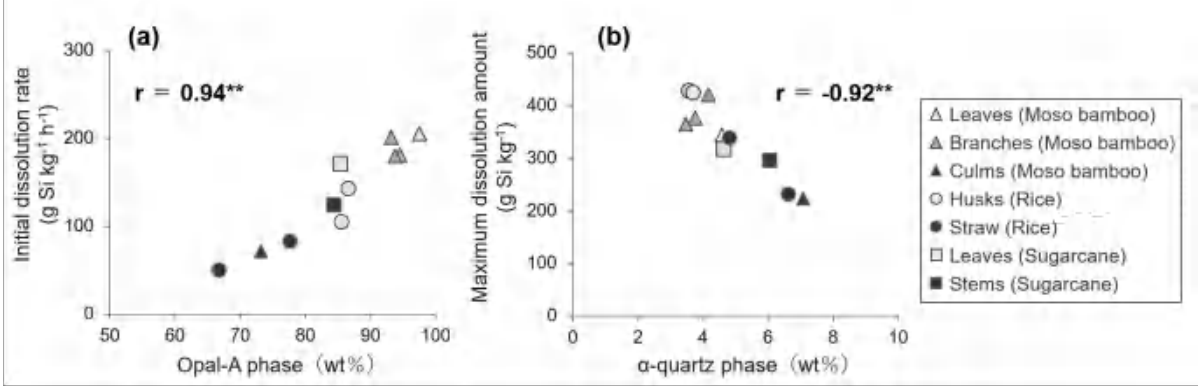



Fig. 1 Relationships between crystallinity and solubility of the phytolith. (a) opal-A phase vs. initial dissolution rate, (b) $\alpha$-quartz phase vs. maximum dissolution amount. **statistical significance at the level of $p < 0.01$

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# Mineralogical Composition of Bulk and Clay Fractions in Mongolian Soils: Insights from X-Ray Diffraction Across Arid to Forest-Steppe Gradients

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**ABSTRACT**

Mongolia's diverse landscapes span forest-steppe, steppe, semi-desert, and Gobi Desert zones, featuring soils influenced by aridic to sub-humid climates, varied parent materials (basalt, sandstone, slate, fluvial/alluvial sediments, dune sands, lake/playa deposits), and pedogenic processes including salinization, sodification, calcification, gypsification, clay illuviation, and redoximorphism. These result in prevalent References Soil Groups such as Solonchaks, Solonetz, Gypsisols, Calcisols, Luvisols, Cambisols, Arenosols, Andosols, and Phaeozems (WRB classification).

This study examines bulk and clay mineralogy via X-ray diffraction (XRD) on selected Mongolian soil profiles from northern forest-steppe (P-series: e.g., P1 Leptic Phaeozem vitric, P2 Vitric Andosol, P3 Sodic Cambisol protocalcic) and southern/southeastern arid/semi-arid regions (X-series: e.g., X1 Gleyic calcic Solonchak sodic, X5 Hypogypsic calcic Gypsisol sodic, X7 Vertic Solonetz takyric, X8 Vertic luvic Calcisol sodic yermic, X9 Calcic Solonetz endoskeletic). Field descriptions document high pH (often 8.5–10.4), elevated carbonates (up to >50% in calcic/petrocalcic horizons), gypsum accumulations (e.g., By, Byk horizons in X5, X6), clay cutans (Btn horizons in X3, X4, X7, X8, P14), vertic features, and gleyic/sulfidic properties in depressions.

The mineral assemblages reflect lithology, aridic moisture regimes, sodium/carbonate accumulation, illuviation, and redox conditions. These findings underscore mineralogical controls on cation exchange, water retention, aggregation, and vulnerability to salinization/sodification in Mongolia's dryland ecosystems, informing sustainable management amid climate change and pastoral pressures.

**Keywords:** Mongolian soils, Mongolian soil bulk and clay minerals

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# A Novel Rainfall-Based Model for Forecasting Soil Moisture Content

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**ABSTRACT**

Growing concerns regarding current methods addressing restrictions in data accessibility and real-world reproduction reinforce the motivation to develop more accurate simulation methods, especially in agricultural sectors. This study utilizes established modeling techniques like the Monte Carlo simulation as well as graphical analysis to account for rainfall unpredictability and foresee volumetric moisture content (VMC) values. This research includes 4 rainfall events measured in Cedar Rapids, Iowa, chosen for its periodic, steady rainfall throughout the year 2025. Key materials used to design the model includes Microsoft Excel spreadsheet as well as publicly available data, primarily from Iowa Environmental Mesonet and United States Geological Survey's National Map tool. Through the utilization of a 5-step process involving the collection of rainfall and soil data, a 4th-degree polynomial regression, application of the Monte Carlo Simulation, and then both exponential decay formula and VMC formula, the compilation and transformation of raw rainfall data aim towards simulating real-world conditions. The Monte Carlo simulation was chosen for its ability to simulate randomness, reflecting the uncertainty in nature. Relative error for one specific data set ranged from -0.873% to +0.695% between the real and simulated values; in addition, the RMSE relative to the values comes extremely close to 0, reaching 0.000344, indicating a superb fit alongside the R^2 of 0.995 for the simulated rainfall intensity. However, the model does stray away from extremely precise values when faced with unexpected surges in rain since the fit for data set 2 saw a R^2 of 0.374, the resultant VMC values are overestimated, seeing high error percentages of 3.91%. With due time, the model may correctly encapsulate and consider numerous natural parameters (e.g. temperature, atmospheric pressure, wind speed) and display a spatial diagram. But the current model can act as the basis to culture the realm of irrigation and agriculture, potentially resolving the current lack of data and uncertainty posed by changing climates.

Keywords: rainfall intensity, Monte Carlo simulation, agriculture, volumetric moisture content

# Modeling the spatiotemporal changes in soil moisture under different vegetation types in the farming-pastoral ecotone of northern China

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## ABSTRACT

Ecotones are transitional zones between two ecosystems, and their sensitivity and fragility make them ideal settings for investigating how community-level interactions respond to global change and anthropogenic disturbance. To address the wide range of ecological problems caused by soil degradation, China has implemented a series of ecological restoration programs since the 1970s, achieving substantial success. However, excessive vegetation restoration has consumed excessive soil moisture, potentially disrupting the fragile ecological balance of the farming-pastoral ecotone of northern China. Therefore, accurately analyzing and predicting trends in soil moisture dynamics under different vegetation utilization types will help to achieve the sustainable development of its ecological environment.

We designed this study to combine the in-situ experiment and the macro-scale regional sampling survey. For the in-situ experiment, we measured soil moisture in grassland (*Stipa bungeana*, etc.), shrubland (*Caragana korshinskii*), and woodland (*Populus simonii*) on steep slopes (with gradient larger than 30°) between 2021 and 2022, and used the Hydrus-1D model to simulate 0–500 cm soil moisture dynamics as affected by vegetation types. We set up different scenarios of vegetation replacement and cover reduction to assess the long-term effects of vegetation management on soil moisture over a 50-year period. Our results revealed significant variations in soil moisture dynamics among vegetation types, with the highest soil moisture observed in woodland and the lowest in shrubland. Notably, a dried soil layer extending beyond 500 cm was observed across all vegetation types. Results from Hydrus-1D modeling indicated that although woodland currently retains more soil moisture than grassland, this pattern will reverse after 21 years. Decreased vegetation cover, irrespective of vegetation type, would lead to soil moisture accumulation. Converting shrubland to grassland would increase soil moisture in the 0–500 cm depth, whereas the impact of converting woodland to grassland depends on vegetation coverage.

In parallel, we conducted a three-round field campaign from 30 July to 25 September 2023, sampling more than 200 sites across the provinces encompassed by the farming-pastoral ecotone of northern China. Soil samples were collected beneath cropland, grassland and woodland, and key physical and chemical properties were measured. We are currently using the aforementioned data and flux data to calibrate vegetation parameters in a biogeochemical model. The findings will provide both theoretical support and practical guidance for the scientific management and sustainable development of ecotone ecosystems.

**Acknowledgments**

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# Soil aggregate stability along a gradient of flooding intensity in the riparian zone: the role of root functional traits

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## ABSTRACT

Soil aggregates serve as the physical foundation for critical ecosystem services in riparian zones, and their stability is intricately linked to the root functional traits during ecological rehabilitation. Flooding, a common stressor in these ecosystems, has great potential to alter plant communities and their functional traits, yet the role of these traits in aggregate turnover and stabilization remains poorly understood. To bridge this knowledge gap, we conducted a thorough investigation into the soil aggregate turnover in a typical riparian zone of the Three-Gorges Reservoir. We closely tracked water level fluctuations and their impacts on vegetation, using undisturbed soil sampling and sieving techniques to assess aggregate size distribution dynamics. Additionally, we employed on-site plant quadrat surveys, minirhizotron observations, and lab analysis of above- and below-ground traits to assess the changes and relative contributions of plant functional traits to aggregate stability. Controlled indoor experiments further explored the mechanisms by which root functional traits influence soil aggregate formation and stability. Our findings revealed that soil aggregate stability decreased significantly with the increasing flooding intensity, but not in a linear fashion. Oxides played a crucial role in aggregate stability under intense flooding, while organic carbon dominated under milder conditions. We observed significant variations in above- and below-ground biomass with flooding intensity, and species diversity had contrasting effects on small macro-aggregate formation. Perennial herbs with fibrous root systems were essential for soil aggregate stability under intense flooding, while plant diversity was critical under milder conditions. Root volume density mediated the effects of plant diversity on riparian soil stability. This study highlights the complex interactions between flooding, plant functional traits, and soil aggregate stability in riparian zones. Root exudate stoichiometry governs soil aggregation through temporally differentiated microbial pathways, with fungi providing sustained structural stabilization while bacteria contributing stage-specific functional reinforcement. Understanding these dynamics is crucial for effective management and restoration of these vulnerable ecosystems. This research will also enhance our understanding of soil aggregate turnover in extreme environmental contexts and the role of vegetation in promoting aggregate formation and stabilization within the soil-plant system.

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# Evapotranspiration varies across different landscape units, influenced by hillslope position, soil properties and vegetation: An example from the Qinghai-Tibet Plateau

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**ABSTRACT**

When mapping soil types based on their spatial arrangement within the landscape, geomorphological features of hillslopes emerge as a key factor. Unlike conventional pedology, hydropedology not only considers these geomorphological predictors but also aims to describe the characteristic hydrological processes for different landscape positions. A critical focus is on soils with differing water regimes, particularly those affected by lateral water redistribution.

In this study, we utilized evapotranspiration as a hydrological variable to assess land-atmosphere interactions in two areas within the Qinghai-Tibet Plateau. We modeled evapotranspiration at a high resolution through satellite remote sensing of surface temperatures combined with the METRIC simulation algorithm for the period 1990 - 2021. To connect evapotranspiration with landscape positions, we employed the LUMP tool, which incorporated geomorphological and vegetation data for clustering. This approach enabled us to identify five representative hillslope types characteristic of the study regions.

For each representative hillslope and each terrestrial unit (comprising representative soil-vegetation columns at a given landscape position), we gathered time series of simulated evapotranspiration. Our findings revealed that soil properties and vegetation significantly affect surface energy exchange processes. Specifically, alpine meadow and wet meadow soils located at the foothills exhibited the highest rates of evapotranspiration (e.g. 0.5 mm h-1 at noon in July), while alpine steppe soils on steep slopes demonstrated the lowest rates (e.g. 0.1 mm h-1 at noon in July).

Vegetation disturbances (assessed through vegetation indexes) had the most considerable impact on the functioning of the alpine steppe soils and were least detrimental to wet meadow soils. Presumably soil properties are instrumental in maintaining stable evapotranspiration rates that correspond to climatic precipitation levels. It can be hypothesized that the mattic horizon proved to be more resilient to disturbances in high moisture conditions compared to low moisture regimes. Furthermore, with vegetation restoration, wet meadows exhibited the quickest rates of evapotranspiration recovery.

Evapotranspiration plays a crucial role in the moisture recycling process that stabilizes the regional water cycle by returning water vaporized from land back as precipitation. Practice of avoiding disturbance at dry areas and wet meadow prioritization in restoration can be useful considering both implementation success and opportunity values.

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# Identifying spatiotemporal patterns of hillslope subsurface flow in an alpine critical zone on the Qinghai–Tibetan Plateau based on three-year, high-resolution field observations

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**ABSTRACT**

The spatial heterogeneity and temporal variability of hillslope subsurface flow (SSF) generation are poorly understood in the alpine critical zone (CZ). Owing to the limitations of observation technology bottlenecks and harsh environments, existing studies lack a holistic and process-based understanding of SSF generation, particularly for the deep CZ and annual freeze–thaw cycle. This study improves the conventional trenching observation scheme and is the first to have successfully monitored SSF processes from the soil to the bedrock layer with high-resolution from 2017 to 2020 in a headwater catchment of the Qinghai–Tibetan Plateau. The results show that hillslope runoff generation exhibited similar trends over the years while exhibiting distinct patterns across seasons. Spatially, slope aspects significantly affect the runoff amount and ratio. The south-facing slope is dominated by overland flow (OF, 84.2–97.0%), while the north-facing slope is dominated by SSF (88.9–97.3%). The runoff depth of the north-facing slope is 11.0 times that of the south-facing slope. The SSF in the deep CZ accounts for 20.8–37.8% of the total runoff along the north-facing slope. Temporally, runoff generation exhibits distinct patterns across seasons. OF exhibits two different patterns, while SSF exhibits five across seasons. Our results indicate that runoff generation in different freeze–thaw stages should be studied by the time phase. Therefore, we propose seasonal or freeze–thaw period-based classification criteria and divide OF and SSF into two and three consecutive periods throughout the calendar year. We suggest that these inferences and observations should be considered in the framework of hydrological models in cold regions.

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# Hydropedological Responses to Anthropogenic Soil Importation and Wadi Channel Narrowing in Arid Oman

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**ABSTRACT**

Wadis (ephemeral watercourses) in arid landscapes act as critical ecohydrological corridors linking soil, water, and geomorphic processes. However, these fragile systems are increasingly subjected to anthropogenic alterations that disrupt soil–water interactions and sediment connectivity. This study applies a hydropedological framework to investigate how soil importation and wadi channel narrowing for agricultural expansion affect sediment dynamics and soil chemistry in Wadi Al-Khoud, Oman. Field sampling across three transects (n = 48), combined with laboratory and spatial statistical analyses, revealed significant modification of surface-soil properties and geomorphic stability. Imported "alien" soils, often containing quarry debris and construction waste, altered the native soil composition—elevating $Na^+$, $NO_3^-$, and $K^+$ concentrations by 249%, 33%, and 104%, respectively, relative to control sites. Textural analysis indicated a 4.3-fold increase in fine silt content at impacted locations, while semivariogram modeling demonstrated disturbed spatial continuity of soil texture and chemistry. Between 2010 and 2020, wadi channel narrowing by an estimated 73 m (≈95,800 $m^3$ of imported material) induced a Venturi-type contraction, amplifying flow velocities, sediment scour, and downstream contaminant dispersal. The formation of nabkhas — vegetation-stabilized sand mini-mounds — illustrates altered hydrogeomorphic feedbacks and ecological instability within the terraced floodplain.

These findings underscore the consequences of unregulated land modification in arid environments, where altered soil–water–geomorphology linkages accelerate land degradation and hydrological risk. Integrating hydropedological concepts into land-use planning and policy is essential to safeguard wadis as "natural hydraulic veins" that sustain soil functions, groundwater recharge, and ecosystem resilience in dryland regions.

**Keywords:** Landscape evolution, dryland hydropedology, soil importation, sediment dynamics, ephemeral streams.

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# Biochar-Induced Changes on Soil Nutrient Retention and Saturated Hydraulic Conductivity of Sandy Loam Soil in Lahar-laden Area of Zambales, Philippines

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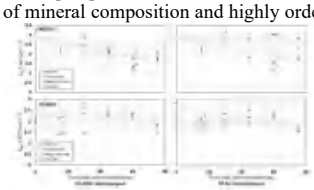
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## ABSTRACT

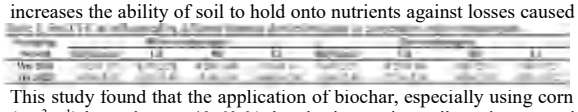
Lahar-laden areas in the Philippines are known to have inherent soil constraints, such as high nutrient leaching and low water holding capacity, which could be attributed to sandy loam texture. Negatively-charged biochar soil conditioner is the bio-product of thermal decomposition of renewable feedstock after pyrolysis. Porosity of the material at 50 and 10 µm diameter can affect soil porosity through modifying soil structural properties via surface roughness and contact angle (Rasa et al., 2018). Many local experiments have been conducted on the benefits of biochar in improving soil macronutrients, beneficial microorganisms, and crop yield. However, there are a limited number of studies on its potential to enhance soil nutrient retention capacity as well as other physical properties such as reduction in bulk density, promotion of aggregate stability, and increase in water retention. The aim of the study is to determine the effect of different crop waste biomass-derived biochar combined with organic fertilizer in improving nutrient retention and saturated hydraulic conductivity in sandy loam soil. The on-farm experiments were established in organic-based Sambali Farm, Brgy. Taugtog, Botolan, Zambales (15.304174 N, 120.048256 E) during the wet season of CY2021 and dry season CY2022 from February 2021 to January 2022. The area has an annual precipitation of 2,896 mm with 26 °C average temperature. The Angeles sandy loam soil type (Typic Ustipsamments) is located in a nearly level area of 3% at 18 m elevation with a soil depth of greater than one meter (m). It has high internal drainage with a saturated hydraulic conductivity (Ksat) of 3.11 x 10 -3 cm3/s and has a low ability to hold exchangeable cations with cation exchange capacity (CEC) of 8.68 cmol(+)/kg. The crop used was hot pepper (*Capsicum sp.)* Red Hot F1 variety. The treatments were arranged in split-plot design with application of organic fertilizer as main plots (V1-V2) and biochars at 0.5 t ha-1 (Marcia et al, 2020) as sub-plots (B1-B4) such as rice hull (Rh), coconut husk (Ch), mango trimmings (Mt) and corn cob (Cc). The plot size was 3m x 6m (18 m$^2$) with 0.5 cm plant distance between rows. Scanning electron microscopy (SEM) surface morphology was performed using Hitachi SU8230 FE-SEM with low vacuum of 30 Pa, voltage 15 kV and 8-15 mm working distance from the detector. Soil CEC and Ksat were analyzed using ammonium acetate and constant head method, respectively. The analysis of variance (ANOVA) was calculated using the Statistical Tool for Agricultural Research (STAR) 2.0.1. Tukey's HSD test (at P<5%) was used for pairwise comparison. Data were further analyzed for seasonal variation and trend analysis.



best pore-defined development compared to Rh and Ch. Mt and Ch biochars had larger structure in biochar provides high adsorption capacity attributed from higher crystallinity of mineral composition and highly ordered aromatic structures form (Kloss et al., 2012).



ts obtained lowest *Ksat* (cm$^3$ s$^{-1}$) of 1.21 x 10-3 cm3/s to 1.87 10-3 cm3/s at 60 dat (VxB, *P* value = 0.0389) except for Rh biochar who had the highest *Ksat* (3.01 x 10$^{-3}$ cm$^3$ s$^{-1}$) for WS 2021. Cc biochar alone obtained the lowest *Ksat* (1.21 x 10$^{-3}$ cm$^3$ s$^{-1}$) with 61 % decrease from the initial 3.11 x 10-3 cm3/s. For DS 2022, *Ksat* only decreased only with the application of Ch biochar with Vc of 1.4 x 10-3 cm3/s at 15 data (VxB, *P* value = 0.0005). Decreasing soil Ksat can improve water holding capacity in sandy loam soil during irrigation events (Nawaz et al., 2019), thereby resulting in the increase in soil water retention. The application of biochar resulted in an increase in CEC in all biomass by greater than 43% from WS 2021 to DS 2022 (Table 1). Rh biochar with Vc, Ch biochar with Vc, and Cc biochar alone obtained an increase in CEC by 80-90%. El-Naggar et al. (2018) also confirmed that porous biochar increases the ability of soil to hold onto nutrients against losses caused by leaching.



This study found that the application of biochar, especially using corn cob biomass in sandy loam increased CEC (cmol$^{(+)}$ kg$^{-1}$) by 80-90 % and decreased Ksat (cm$^3$ s$^{-1}$) by as low as 40-60 % thereby improving soil nutrient retention and decreasing the saturated hydraulic conductivity of Angeles sandy loam in two (2) cropping seasons. Induced improvement on soil properties of sandy loam soil were attributed to the porous morphology of corn cob biochar affecting soil porosity through modification of soil structural properties via direct mechanisms for surface roughness and contact These findings are important because it provided evidence on the efficacy of crop wastes derived-biochar in improving the ability of the soil to retain nutrients and residence time of irrigation in sandy loam soils in lahar-laden areas; and consequently, it may reduce the amount of applied fertilizer and mitigate the effects of drought.

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# Addressing water security in DOCG vineyards: a hydropedological framework linking soil water balance, plant stress, and berry quality

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**ABSTRACT**

Climate change is severely impacting viticulture in Southern Italy, threatening the economic sustainability of autochthonous varieties like Greco (DOCG) due to increasing drought and thermal stress. Addressing this real-world challenge requires moving beyond empirical observations to a robust hydropedological framework capable of predicting Soil-Plant-Atmosphere (SPA) interactions under future scenarios. This study, part of the GREASE project, presents an interdisciplinary approach applied to a 3-year field experiment (2020-2022) in a Greco vineyard (Avellino, Italy) on a Calcaric Cambisol.

The methodology integrated pedological characterization with the calibration of the agro-hydrological model SWAP. By monitoring soil water content, leaf water potential, and grape quality across different soil (tillage vs. cover crops) and canopy management treatments, the model was validated to simulate the Crop Water Stress Index (CWSI). Crucially, the study identified a specific hydropedological threshold: maintaining a CWSI below 20% at veraison is mandatory to achieve "Ultra Quality Grapes" (UQG) with the optimal sugar/acidity balance. Conversely, stress levels exceeding this threshold led to a significant quality degradation (from Standard to Low Quality), regardless of the soil management adopted, demonstrating that soil management alone is insufficient to mitigate the climate signal. Applying this validated model to future climate scenarios (RCP 4.5 and 8.5), results forecast a progressive rise in water stress (up to +14% by 2100 in RCP 8.5), pushing rainfed vines frequently above the safety quality threshold.

These findings indicate that a transition from rainfed to irrigated viticulture is becoming essential in this pedoclimatic context. The proposed hydropedological modelling approach provides the quantitative basis to redesign irrigation strategies, ensuring the resilience of prestigious wine-growing areas by linking soil hydraulic properties directly to oenological goals.

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# Runoff and Sediment Response to Rainfall and Vegetation Cover in the Toutun River Basin（Xinjiang,China）

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**ABSTRACT**

The characteristics of precipitation events, vegetation type, and soil physical properties (including moisture content) are primary factors influencing slope surface runoff generation and soil erosion. Vegetation is a critical factor in mountainous areas due to its role in precipitation redistribution and its profound effects on soil physical properties and moisture content, thereby significantly influencing surface runoff yield and soil erosion.

To elucidate the mechanisms underlying these effects, experimental runoff plots were established in *Picea schrenkiana* var. *Tianschanica* forests at three elevations (1,800 m, 2,200 m, and 2,600 m) in the mid-reach of the Toutun River Basin, Tianshan Mountains (Xinjiang, China). At each elevation, control plots were installed in adjacent grasslands, resulting in a total of 36 plots. A bare ground control was omitted primarily because the natural landscape is predominantly grassland (excluding bare rock), and the grasslands are privately owned by herders, making large-scale destructive experiments unfeasible.

From May to September 2025, long-term monitoring equipment recorded 44 rainfall events and corresponding soil moisture dynamics. Runoff and sediment yield were observed for 16 of these events, leading to the following conclusions: (1) The frequency, amount, and intensity of rainfall events varied with elevation, and the response of soil moisture content at different depths also varied across rainfall event magnitudes; (2) The canopy of *Picea schrenkiana* var. *Tianschanica* significantly altered the amount, intensity, and kinetic energy of throughfall, consequently reducing runoff and sediment yield on forested slopes; (3) Short-duration, high-intensity rainfall events, though infrequent, contributed minimally to soil moisture recharge but had the potential to generate substantial runoff and sediment in a very short period, representing a key concern for geohazard prevention in the region.

In recent years, global climate change has significantly altered the frequency and characteristics of rainfall events in arid mountainous regions. Notably, short-duration, high-intensity events have become more frequent, leading to an increase in associated natural disasters such as flash floods and debris flows triggered by surface runoff and soil erosion. This study investigates the characteristics and patterns of rainfall events and their impacts on runoff and sediment yield under different vegetation covers in the mid-reach of the Toutun River Basin. The findings aim to provide a theoretical basis for research on soil hydrological processes and for the development and parameter calibration of hydrological models in arid mountainous regions.

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# Spatiotemporal variations and driving factors of groundwater ecosystem service value in a typical arid region:A case study of the Xinjiang, China

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## ABSTRACT

Groundwater is a vital component of the hydrological cycle, playing a crucial role in meeting the water demands of humans and ecosystems, and an important resource for maintaining economic and social development (Gu et al., 2018; Li et al., 2019). Particularly in arid regions, there are often severe water shortages and uneven seasonal distribution issues(Fang et al., 2021). When surface water and precipitation are insufficient, groundwater serves as a buffer and is especially relied upon in arid areas to meet heightened water demands under climate warming (Condon et al., 2020; Xiao et al., 2018). However, in arid regions, the ecological environment is already fragile, and coupled with the impact of arid climate and human activities, makes groundwater resources susceptible to change, which posing serious challenges to water supply and ecological security (Rohde et a2024). Therefore, understanding the actual situation of groundwater resources and analyzing service value they bring to humans is to provide scientific support for protecting and optimizing ecosystems in arid areas. Although scholars have studied the groundwater ecosystems service value (GESV) in recent years (Cital et al., 2025), these studies mainly focused on economically developed regions and have been limited to construction of indicator systems and temporal evolution of service value. However, they have not further discussion on scale effects, spatial characteristics, and driving factor analysis. This indicates that GESV deserves further research.

Xinjiang Uygur Autonomous Region (Xinjiang) is one of the extremely arid regions in the world and an ecologically fragile area (Li et al., 2021). The region has scarce precipitation, extremely high evaporation, and surface rivers with frequent interruptions and strong seasonality, making it almost impossible to form a stable and reliable surface water source(Li et al., 2022). In this extremely arid environment, people's production and daily life mainly rely on use of groundwater resources, and surface ecology mainly depends on groundwater. Therefore, groundwater occupies an irreplaceable position. According to statistics, the total water resources of Xinjiang in 2020 were about 80.1 billion $m^3$, of which 50.35 billion $m^3$ were groundwater resources. The exploitable groundwater resources reached 25.2 billion $m^3$, accounting for about 50% of the total groundwater resources (Xinjiang Water Resources Bulletin,2020). However, with climate change, rapid population and economic growth, the groundwater level in Xinjiang has significantly decreased in recent years (Guo et al., 2021). This has precipitated a series of ecological and environmental issues, including land subsidence (Fan et al., 2023), water quality deterioration(Yan, 2022), surface vegetation degradation (Chen et al., 2015), shrinking lakes and wetlands (Nie et al., 2023), and land desertification and salinization(Yu et al., 2022). To address this crisis, the government has implemented the most stringent water resource management systems to govern groundwater ecosystems(Jiao et al., 2025; Lin, 2021). Looking ahead, projected future climate change is expected to shift glacial meltwater peaks toward decline while significantly increasing surface runoff uncertainty (Farinotti et al., 2015; Huss and Hock, 2018). Groundwater will remain a critical water resource participating in the hydrological cycle and supporting both natural ecosystems and human communities in Xinjiang (Guo et al., 2021; Xiao et al., 2022). In addition, as a water tower in Central Asia, the dynamic changes of groundwater in the Tianshan Mountains of Xinjiang have an impact on the surrounding areas through hydrological cycles and ecosystem chains (Shang et al., 2016). In this context, researching the groundwater ecosystem service value (GESV) of Xinjiang is of great significance.

This study will take Xinjiang, a typical arid region, as the research area. Based on GIS technology, a monetary quantitative value assessment model will be used to investigate the spatiotemporal distribution and hot and cold spot distribution characteristics of water supply (WS), water purification (WP), carbon absorption (CA), and total groundwater ecosystem service value (GESV) of Xinjiang's groundwater ecosystem at the regional, sub regional (North, South, East Xinjiang), and administrative regional scales from 2005 to 2022. Using a geographic detector model, we focused on studying the natural environment and socio-economic driving factors of GESV, and proposed policy recommendations.

**Conclusions:** As for spatiotemporal characteristics, except for WS, the other WP, CA and GESV presented similar spatial pattern, showing a gradual decrease from northwest to southeast. high value and hotspot areas are primarily concentrated in the western Tianshan Mountains and the southern foothills of the Tianshan Range, specifically in oasis regions such as the Ili Kazakh Autonomous Prefecture, the Bortala Mongol Autonomous Prefecture, and Aksu Prefecture. Low value and coldspot areas are primarily distributed in Eastern Xinjiang, specifically in Turpan and Hami citys. From 2005 to 2022, the GESV in Xinjiang showed a trend of increased first and then decreased, with average GESV of 39.22 thousand yuan/$km^2$. The size of GESV at the subregional scale follows the order of Northern Xinjiang > Southern Xinjiang > Eastern Xinjiang, accounting for 60%, 30%, and 10% of the total GESV in Xinjiang, respectively.

As for driving factors, GESV is influenced by both natural environmental factors and socioeconomic factors. Among them, the interaction between population density, per capita GDP, and other natural environmental factors has the greatest impact on GESV, especially when combined with precipitation, with a q value close to 1. With urbanization and economic development, the impact of human activities on GESV is becoming increasingly evident, leading to the expansion of cold spot areas.

As for policy recommendations, based on characteristics and water usage conditions of different regions in Xinjiang,relevant water resource management measures and policies shall be implemented in a differentiated manner. Strictly control and reduce excessive groundwater extraction in accordance with total volume control targets. To achieve dynamic monitoring of groundwater, in order to forecast, monitor, analyze, and manage the groundwater ecosystem based on the obtained dynamic monitoring data.

**Keywords:** Multiscale; spatiotemporal characteristics; driving factors; groundwater ecosystem service value; Xinjiang

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# Non-monotonic Snow Cover Control on Frozen-Soil Hydrothermal Regimes and Spring-drought Propagation in a Warming Semi-arid Forest Steppe

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**ABSTRACT**

Seasonally snow-covered, seasonally frozen landscapes of north-eastern China are both sentinel regions of climate change and emerging hot-spots of spring drought. Integrating 12 years (2014–2025) of in-situ hydro-meteorological records, multi-source snow data, and soil temperature-moisture observations at the Saihanwula Forest Ecological Station (southern Greater Khingan Mountains, 43°59′–44°27′N, 118°18′–118°55′E, 1300–1400 m a.s.l.), we quantify how snow-cover metrics modulate soil freeze–thaw (FT) dynamics and subsequent spring drought risk.

1. A clear inverted-U response links snow-cover duration (SCD) to the FT period. Medium-snow winters (85–100 mm SWE, 135–150 snow days) prolong FT to 201.0 ± 19.5d, whereas low-snow (<85 mm SWE) and high-snow (>100 mm SWE) winters shorten it to 193.5±7.5d and 193.3±16.2d, respectively. Snow-water equivalent (SWE) is negatively correlated with daily FT rate ($r \approx -0.72$), but the relationship saturates under high-SWE conditions.

2. Process-level diagnostics reveal three distinct regimes:

(i) Low-snow: rapid freezing (1.87±0.68 cm $d^{-1}$) and rapid thawing (2.78±0.98 cm $d^{-1}$) with limited latent-heat buffering;

(ii) High-snow: delayed freeze onset (up to 37d) and earlier thaw completion due to a strong insulation effect at the soil–snow interface;

(iii) Medium-snow: optimal energy balance and hydro-thermal synchrony, maximizing pre-spring soil-water storage ($\theta_v \approx 0.20–0.25$ $m^3m^{-3}$ in 0–40 cm).

3. Coupled snow-frozen-ground degradation amplifies spring-drought propensity. Warmer winters shorten SCD and advance snow-off, truncating the FT window and triggering:

(a) Hydrological-timing mismatch: earlier snowmelt precedes soil thaw, reducing infiltration fraction from 0.62 to 0.38;

(b) Intensified process intensity: higher spring evapotranspiration demand paired with thinner, earlier thawing soil layers increases root-zone water deficit;

(c) Compressed eco-hydrological window: the period with simultaneously unfrozen soils and available snowmelt shrinks significantly.

Consequently, the probability of moderate-to-severe spring drought rose markedly over the study period. These findings demonstrate that non-linear snow-cover feedbacks govern frozen-ground hydrothermal behaviour and spring drought trajectories in cold semi-arid regions. We propose a SWE-based early-warning threshold (20±3 cm) for adaptive water-resource and forest-management strategies under continued warming.

**Keywords:** Seasonal snow cover; Seasonally frozen soil; Spring drought; Freeze–thaw; Non-linear feedbacks; Semi-arid cold region

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# Irreversible soil carbon and nitrogen loss during the thermokarst lake succession under climate change in the Tibetan Plateau

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## ABSTRACT

Thermokarst lake development induced by abrupt permafrost thaw disrupts soil carbon and nitrogen cycling, potentially creating a strong positive feedback to climate warming. However, TL impacts on active-layer soil organic carbon (SOC), total nitrogen (TN), and the C:N ratio—particularly across different successional stages—remain inadequately quantified. Furthermore, the unknown roles of local factors and climatic backgrounds severely limit fine-grained predictions of TL-affected carbon and nitrogen responses to future climate change. Here, we investigated eleven TLs on the Tibetan Plateau, including expanding, stable, drying, and drained types characterized by distinct thermokarst microfeatures. We found that, unlike in high-latitude regions, TLs in this warmer, drier alpine setting predominantly caused SOC, TN, and C:N losses, and the most severe declines occurred at the drying and drained stages, suggesting that degenerating TLs are potential hotspots for greenhouse gas emissions. Multi-scale analysis revealed that at the landscape-scale, microfeatures, sand, soil water (SW), pH, and aboveground biomass explained over 50% of the variance in SOC, TN, and C:N at most sites; importantly, the microfeature independently contributed the most, and the effect of local SW shifted from positive at drier sites, likely by mitigating water stress, to negative at wetter sites, likely by exacerbating erosion. Regionally, background factors (climate, grazing, and soil/vegetation properties of controls) explained over twice the variance in carbon and nitrogen metrics compared to within-landscape factors, with the background SW exhibiting the strongest effect. Projections incorporating climate-driven cascading effects through SW and pH showed that while future trajectories varied by TL stage, historical TL-induced C and N losses (relative to controls) were likely irreversible under SSP climate scenarios. Our study provides a mechanistic framework for parameterizing fine-scale thermokarst processes—accounting for microfeatures and key hydro-climatic drivers—currently underrepresented in Earth System Models, thereby constraining a key uncertainty in projecting the permafrost carbon-climate feedback.

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# Deciphering Soil Water-Carbon Coupling in the Earth's Critical Zone and Its Environmental and Edaphic Controls

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**ABSTRACT**

Soil hydrologic processes support ecosystems, regulate the impact of climate change on terrestrial systems and govern feedback mechanisms between water, energy and biogeochemical cycles (e.g., carbon). Soil water-carbon dynamics are two processes that interact to control soil's ecological functions. Although soil water and carbon are tightly coupled in the Earth's Critical Zone (CZ), their coevolution across eco-climatic gradients remains underexplored. The growing availability of harmonized, long-term observations from the National Ecological Observatory Network (NEON) in the United States offers a unique opportunity to examine how hydrologic regimes shape soil carbon storage and turnover, and how carbon dynamics in turn modify soil physical and hydraulic properties. In this study, we leverage NEON soil moisture, temperature, soil organic carbon, and ecosystem flux measurements across contrasting terrestrial ecosystems to investigate the joint dynamics of soil water and carbon across spatiotemporal scales and evaluate how hydroclimatic and site-specific factors (e.g., soil, vegetation, topography) modulate carbon responses to moisture. By framing soil water and carbon as coevolving components of the CZ, this work advances a process-based understanding needed to improve predictions of carbon–water feedbacks under a changing climate and to inform soil and land management strategies aimed at enhancing ecosystem resilience.

**Acknowledgments**

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# Paddy cultivation history affects soil water dynamics and water balance by altering soil physical and hydraulic parameters

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## ABSTRACT

Accurate quantification of the water balance is essential for optimizing irrigation and minimizing nutrient loss in paddy fields. However, the effect of cultivation history on the water balance dynamics remains poorly understood. This study examined three paddy fields with different cultivation ages: a very young paddy field (VYPF, 10 years), a young paddy field (YPF, 27 years), and an old paddy field (OPF, > 100 years). In-situ field monitoring (including soil water content (SWC), plant growth indices, and meteorological data) combined with HYDRUS-1D simulations from October 2017 to October 2019 was used to quantify the water balance and identify water-saving potential. The model effectively reproduced observed SWC and water balance components. Compared with YPF and VYPF, OPF exhibited higher SWC at 10 cm and 60–90 cm depths but lower SWC at 20–60 cm. Substantial differences were observed among the three fields in percolation, groundwater capillary rise, and surface runoff, particularly during the rice-growing period. In VYPF, percolation and groundwater capillary rise accounted for 53% and 24% of total water input (rainfall + irrigation), respectively—values that exceeded those of YPF (39% and 18%) and OPF (14% and 9%). Conversely, runoff in OPF (25%) was markedly higher than in YPF (7%) and VYPF (6%). These differences reflect the effects of cultivation history on soil physical and hydraulic properties. Prolonged paddy cultivation increased bulk density in the plow pan and reduced saturated hydraulic conductivity, thereby impeding vertical water flow and enhancing surface water retention. Overall, the results highlight that the assessments of water balance and the design of water-saving irrigation strategies in paddy systems must explicitly account for cultivation duration.

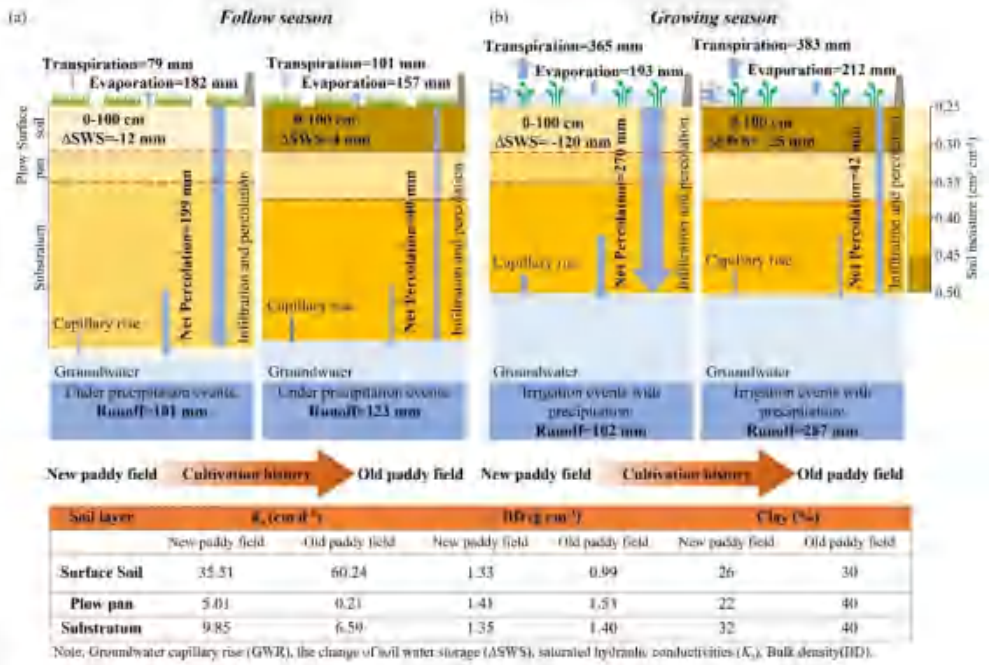



**Figure 1** Conceptual model illustrating changes in water balance components and soil properties with increasing cultivation history. Note: values of water balance components represent averages from 2018 and 2019. Panels (a) and (b) correspond to the fallow and growing seasons, respectively. Yellow rectangles denote soil water content. The change in soil water storage indicates the difference between initial and final water volumes within the soil profile during the respective fallow or growing periods.

**Keywords:** Plow pan, Deep Percolation, Groundwater capillary rise, Runoff, HYDRUS-1

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# Modelling water retention curves for hydrophobic granular soils

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## ABSTRACT

Hydrophobic granular soils, which may develop under natural conditions or through artificial processes, resist or redirect the infiltration of water into the soil matrix. Due to reduced surface wettability, soil water repellency leads to unstable wetting behaviour and the formation of preferential flow paths. While water retention curves (WRC) are important for predicting the hydraulic behaviour and the associated mechanical response, it is difficult to accurately determine them for hydrophobic granular soils. One approach to predict the WRC is therefore to model the particles, pore space, and fluid interaction analytically. Most studies assume smooth spherical particles for the soil particle-water interactions and capillary force calculation. However, the water retention behaviour of hydrophobic granular soils is closely related (via capillary phenomena by Young-Laplace equation) to the symmetry or asymmetry of the pinned water bridges, which is, in turn, governed by the particle surface geometry and orientation. This research therefore aims to develop geometry-aware model framework for determining WRC in hydrophobic granular soils. Different particle shapes (sphere, cube, triangular prism) are investigated to represent realistic soil geometries which alter the morphology of the water bridge. Surface Evolver Software is used to simulate the water bridge morphology for various particle shapes, orientations and sizes. Capillary forces associated with water bridges formed between spherical/cubic glass beads were experimentally measured using a tensiometer (DCAT-25). The force-distance curves and videos of the water bridge's evolution during the measurement process were subsequently obtained. Image analysis was then carried out in Fiji to extract the water-bridge profiles, from which the Laplace pressure was determined. The experimental results show consistency with results previously reported in the literature. The simulation results of the water bridge pressure dynamics show agreement with the corresponding values derived from the experimental data.

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# Coupling relationships and threshold effects between vegetation cover and soil moisture across eco-geographical zones on the Loess Plateau.

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**ABSTRACT**

While large-scale vegetation restoration on the Loess Plateau has yielded significant ecological benefits, it has concurrently exacerbated regional water consumption, making the constraints on ecosystem sustainability a critical scientific issue. This study aims to systematically reveal the dynamic coupling mechanisms between vegetation cover (NDVI) and soil moisture (SM) and to construct an NDVI-based ecological threshold system to provide a quantitative basis for optimizing regional vegetation restoration. Based on eco-geographical zoning using a Self-Organizing Feature Map (SOFM) neural network, we analyzed the spatiotemporal evolution and interactions of NDVI and SM by integrating trend analysis, nonlinear Granger causality tests, and the constraint line method. The results indicated that while 96.7% of the region exhibited a significant increasing trend in NDVI, 61.1% showed a decreasing trend in SM, highlighting intensified water resource constraints. Furthermore, a bidirectional nonlinear coupling relationship between NDVI and SM was observed in 97.9% of the area. Notably, this study is the first to reveal a four-stage nonlinear coupling pattern defined by three key ecological thresholds ($\theta_1$,$\theta_2$,$\theta_3$), which sequentially characterize the ecosystem's transition through states of water accumulation, water competition, optimal balance, and ecological overload. The spatial differentiation of the ecological overload threshold ($\theta_3$) quantitatively characterized the constraints on vegetation growth across different zones (e.g., 0.526 in the driest zone R1; 0.669 in the wettest zone R4). An assessment based on this threshold system revealed that 94.9% of the arid zone (R1) is currently in the water competition phase, whereas parts of the high-altitude zones (R5, R6) face high risks of ecological overload. Accordingly, we propose zonal regulation strategies targeting overloaded zones (thinning), balanced zones (enclosure), and potential zones (afforestation), offering refined management bases and methodological guidance for ecological restoration in the Loess Plateau and similar arid to semi-arid regions globally.

**Key words:** Vegetation restoration; Soil moisture; Synergistic evolution; Bidirectional feedback; Threshold analysis

**Acknowledgments**

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Sincere gratitude is extended for the support provided by all the aforementioned funded projects!

# Divergent ecohydrological adaptation mechanisms of restored vegetation driven by micro-topography: Structural decoupling, hydro-thermal trade-offs, and competitive depletion

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**ABSTRACT**

In arid and semi-arid regions, soil moisture is a key factor limiting vegetation growth. Micro-topography significantly influences habitat heterogeneity by regulating water and heat redistribution. However, the mechanisms by which different restored vegetation restoration patterns (tree plantations, shrublands, and grasslands) adapt to this process via differentiated ecohydrological pathways remain unclear. This study conducted community surveys and soil moisture measurements (0-100 cm) on tree plantations, shrublands, and grasslands across different micro-topographies (slope aspect and position) on the Loess Plateau. The Difference Ratio of Soil Moisture (DRSM) and Structural Equation Modeling (SEM) were employed to quantify ecohydrological interactions. Results indicated that: (1) Slope aspect dominated soil moisture distribution ($\beta > 0.85$), forming "water resource patches" on shady slopes and lower slope positions; (2) Grassland diversity was positively driven by soil moisture ($\beta = 1.22$), whereas coverage was insensitive. Shrub canopy expansion showed high dependence on moisture ($\beta = 1.88$) but was subject to direct topographic inhibition. Tree growth exhibited a significant negative correlation with soil moisture ($\beta = -0.38$), with analysis revealing significant moisture depletion in the 60-100 cm soil layer; (3) Overgrowth of woody plants exerted a significant inhibitory effect on understory herbaceous diversity through resource competition ($\beta = -0.50$). This study reveals distinct adaptation mechanisms: grassland direct dependence, shrub trade-off adaptation, and tree competitive consumption. Future ecological restoration practices should shift from single coverage indicators to refined configuration strategies based on "micro-topography–water carrying capacity" to maintain the long-term stability of regional ecosystems.

**Key words:** Micro-topography; Soil moisture; Vegetation restoration; Ecohydrology; Loess Plateau

**Acknowledgments**

This research was supported by the following projects: the Special Topic of the National Key Research and Development Program of China titled "Multi-element, Multi-level and Precise Small Watershed Classification Based on Space-Air-Ground Integration (2023YFF1305105)"; the Key Program of the Shaanxi Provincial Natural Science Basic Research Plan titled "Study on Vegetation Stability Analysis and Key Technologies for Structural Optimization in the Loess Plateau of Northern Shaanxi (2025SYS-SYSZD-006)"; the Special Program for Serving Local Development of the Shaanxi Provincial Department of Education titled "Evaluation of Ecosystem Quality, Change Trends and Resilience in Typical Regions (24JE003)"; and the General Program of the National Natural Science Foundation of China titled "Evaluation and Model Construction of Slope Vegetation Restoration in the Loess Hilly Region Based on Slope Position Characteristics (41871190)".

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# Process-Oriented Watershed Delineation in Human-Modified Plain Farmlands: Key Constraints and Recent Advances

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**ABSTRACT**

Due to gentle topography, ambiguous watershed divides, and intensive human disturbances, traditional terrain-driven watershed delineation methods often fail to capture the actual organization of hydrological processes in plain regions. Farmland-dominated landscapes, representing a transitional system between natural and highly engineered urban environments, have profoundly reshaped runoff generation, connectivity, and flow pathways through irrigation, tillage, and artificial drainage networks. As a result, hydrological responses may initiate locally before being expressed at the catchment outlet, challenging the conventional use of static watershed units.Following the logic of "problems–progress–direction", this study systematically reviews the core challenges and recent advances in watershed delineation for plain farmland regions. We identify three fundamental constraints: (i) limited adaptability of terrain-based algorithms under weak relief and strong human modification, (ii) insufficient quantification of coupled natural–human controls on hydrological connectivity, and (iii) mismatches between data resolution, process scale, and scientific objectives. Correspondingly, we synthesize three major research pathways, including algorithmic innovations, dual natural–human coupling frameworks, and scale-adaptive data strategies.We argue that watershed delineation in human-modified plain farmlands should be reframed as a process-oriented and demand-driven endeavor, shifting from static topographic units toward event-driven, functionally relevant hydrological units that better reflect where and how hydrological and soil-related risks are initiated.

# Redistribution of hydrological and dissolved nutrient by self-organized shrubs: strategies to collect rain and nutrient for surviving in drylands

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**ABSTRACT**

Rainfall redistribution by vegetation and associated dissolved nutrient fluxes are critical for water and nutrient cycling in plant-soil system. Shrubs are the dominant vegetation type and show contrasting morphological characteristics in drylands, self-organized being clumped with aggregated canopy or scattered with isolated canopy. However, little is known about the effects of shrub self-organization on rainfall redistribution and dissolved carbon and nitrogen fluxes (DC, DN), which further affects soil moisture recharge and soil nutrient accumulation to resist drought. In this study, we compared water fluxes (including throughfall, stemflow, infiltration, surface runoff, and top-soil moisture) and their DC and DN fluxes between the clumped and scattered shrubs of *Salix psammophila* on the Loess Plateau in China from 2019-2021. The scattered shrubs had a significantly higher throughfall percentage (77.6% vs. 72.5%), but a lower stemflow percentage (5.4% vs. 7.9%) and surface runoff percentage (0.10% vs. 0.37%) compared to clumped shrubs. Moreover, clumped shrubs demonstrated significantly higher DC flux in stemflow, yet lower fluxes in runoff compared to scattered shrubs ($p < 0.05$), while no significant difference of fluxes in throughfall and infiltration was observed. The clumped shrubs had significantly higher plant-derived DC and DN fluxes than those in scattered pattern ($p < 0.05$), whereas there was no significant difference of soil-buffered fluxes between the two patterns. Thus, scattered shrubs collected more net rainfall resulting in higher surface soil moisture, whereas clumped shrubs received greater amount of nutrient inputs leading to increase of soil nutrient content in surface layer. This study reveals the contrasting patterns of self-organized shrubs to harvest rainfall and dissolved nutrient, which provides a new understanding on the survival strategies of xerophytic shrubs from morphological adaptations in drylands.

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# Pore Architecture, Water Dynamics, and Climate Sensitivity of Mountain Volcanic Soils: Integrating SEM–DIA and NMR Relaxometry for Hydropedological Assessment

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## ABSTRACT

Mountain soils are inherently fragile systems and exhibit heightened susceptibility to shifts in temperature and precipitation associated with ongoing climate change. Among the factors controlling their hydrological behavior, porosity, permeability, and the physicochemical interactions between soil matrices and water are fundamental, as they regulate water storage, transport, and connectivity. In particular, volcanic Andosols show exceptionally strong relationships with soil water retention due to their abundance of short-range–order minerals (e.g., allophane and imogolite), high specific surface area, and complex microaggregate structures, which collectively confer outstanding water-holding capacity and make these soils critical natural reservoirs in mountain environments.

In this study, twelve volcanic soils, Andosols, from a high-altitude grazing area in the central–southern mountain chain of Italy, were analyzed to investigate how variations in thermo-pluviometric regimes influence the physicochemical processes governing water movement, pore-type distribution, and pore-network architecture. Porosity was quantified using Digital Image Analysis (DIA) applied to thin sections of soil micro-aggregates acquired through scanning electron microscopy (SEM). Two-dimensional reconstructions generated from secondary electron and backscattered electron images enabled detailed estimation of pore-size distributions using ImageJ software. Hydrological connectivity, water-molecule mobility, and the interaction of water with soil surfaces were further assessed through Fast Field Cycling (FFC) Nuclear Magnetic Resonance (NMR) relaxometry, providing complementary insights into pore accessibility and fluid–solid interfacial phenomena.

Image analysis identified pore diameters spanning from 2 to >200 μm and revealed three principal pore-shape classes: rounded, elongated, and intermediate. Preliminary results showed a marked predominance (90–95%) of small elongated pores (2–15 μm), indicative of high microporosity and asymmetrical pore geometry. Larger rounded and intermediate pores were found mainly in the 50–200 μm range. NMR relaxometry independently detected three distinct water-mobility domains that aligned closely with the major porosity classes identified by DIA, corroborating the structural–functional relationships within the pore system.

The combined application of SEM–EDS imagery, DIA, and NMR-based hydrological metrics demonstrates strong potential for high-resolution soil pore characterization and for integrating structural and functional soil information. Crucially, this analytical framework enhances the capacity of current research efforts to anticipate climate-driven impacts on soil processes and water availability, particularly in mountain environments—key regions for freshwater supply—thus contributing to a better understanding of how future climatic shifts may alter hydrological security and soil–water interactions.

# Infiltration-Runoff Processes in Soil-Epikarst Systems on Karst Hillslope in Southwest China

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## ABSTRACT

Karst landscapes developed on carbonate rocks are characterized by inherent properties such as slow soil formation rates, shallow soil layers, and exceptionally high permeability, which collectively drive rapid hydrological responses. This fast water-rock interaction mechanism enhances regional groundwater recharge potential while simultaneously exacerbating the risks of flooding and drought. However, due to the high spatial heterogeneity and procedural complexity of karst systems, significant gaps remain in understanding the pathways, fluxes, and regulatory mechanisms of hydrological processes.

To address these knowledge gaps, we employed an integrated observational approach using three-dimensional hillslope monitoring plots, combining high-resolution hydro-meteorological measurements with water-isotope tracing methods. This methodology enabled systematic quantification of hydrological processes from soil layers through the epikarst zone.

Our series of studies reveal that due to the high soil permeability in karst slopes, surface runoff generation is limited (runoff coefficient <5%), with hydrological processes being predominantly subsurface-dominated. Rainfall infiltration in the soil is characterized by exceptionally rapid wetting front movement (1373 mm/h), significantly faster than in non-karst regions (17-610 mm/h). While macropore flow serves as the primary preferential flow pathway, the prevalence of soil-rock interface flow represents a distinctive phenomenon in karst systems. Surface runoff is only triggered when rainfall intensity exceeds the soil infiltration capacity and rainfall volume surpasses soil storage capacity; though during extreme rainfall events, infiltration-excess runoff may dominate—constituting a critical component of flood peak formation. Soil thickness is a key structural factor influencing infiltration-runoff processes, regulating infiltration rates, pathways, and response times. As soil thickness increases, the impact of topography on hydrological processes gradually diminishes. Following vegetation restoration, runoff reduction is attributed to enhanced canopy interception and improved root-zone water storage capacity, thereby strengthening soil and water conservation functions. Accordingly, this research advances the theoretical framework of karst hydrology and offers crucial insights for water resource management, disaster risk reduction, and ecological restoration evaluation in karst regions under changing climate conditions. Future work should integrate multi-scale modeling approaches to extend hillslope insights to catchment-scale water security strategies.

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# An Eco-Friendly Dual-Tracer Method Combining Synthetic DNA Fragments and Heat for High-Resolution Characterization of Aquifer Hydraulic Conductivity

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## ABSTRACT

Accurate characterization of aquifer hydraulic heterogeneity is essential for understanding water flow, solute transport, and contaminant migration in subsurface systems, yet remains challenging due to limited observation density, tracer detectability, and environmental constraints. Conventional chemical tracers, such as fluorescent dyes and ionic solutes, are often restricted by toxicity concerns, regulatory limits, or insufficient sensitivity, which compromises inversion stability and spatial resolution.

In this study, we present an eco-friendly dual-tracer tomography framework that integrates synthetic DNA fragments and heat to achieve high-resolution characterization of hydraulic conductivity in heterogeneous aquifer media. The approach exploits complementary transport physics: heat provides diffusive, large-scale structural information, while DNA tracers act as advection-dominated, path-stable tracers that preserve sharp travel-time signals. A physics-informed inversion strategy based on travel-time tomography and cross-initialization was developed to fuse both tracer datasets without imposing arbitrary smoothing constraints.

The method was validated in a controlled two-dimensional heterogeneous sandbox aquifer composed of layered sands with strong hydraulic contrasts. Independent thermal, DNA, and dye tracer tomography experiments were conducted, followed by dual-tracer fusion inversions. Model performance was evaluated using twelve independent steady-state pumping tests. Results show that DNA-dominant inversions constrained by thermal priors achieved the highest predictive accuracy ($R^2$ = 0.80, RMSE = 0.95 cm, MAE = 0.67 cm), significantly outperforming single-tracer inversions and dye-based fusion approaches. Thermal-dominant inversions constrained by DNA priors also expanded reliable imaging zones and improved prediction accuracy relative to thermal-only cases.

The proposed framework resolves the trade-off between imaging resolution and environmental sustainability by replacing toxic dyes with biodegradable DNA and residue-free thermal tracers. This strategy enables scalable, high-fidelity subsurface imaging using sparse observation networks, offering a promising tool for soil and groundwater studies in environmentally sensitive settings.

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# Interactions between pollutants, antibiotic resistance and pathogens during transition from untreated to treated wastewater irrigation: a multiscale approach

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## ABSTRACT

To increase the efficiency of water use in agriculture, wastewater reuse for irrigation is common and becomes increasingly imperative, particularly in semiarid areas. Irrigation often starts with untreated wastewater. Yet, water treatment prior to its use in agriculture is needed to reduce environmental and health risks. However, while replacing untreated wastewater with treated water will reduce the loads of nutrients, carbon and many pollutants that reach irrigated fields, it can increase the fraction of multiresistant bacteria released into the environment and mobilize legacy pollutants accumulated in soils. Therefore, we hypothesized that unforeseen risks arise from the implementation of conventional wastewater treatment in long-established wastewater irrigation systems, due to *i)* the mobilization of pollutants that have been accumulated in soils leading to concentrations, leading to *ii)* an increased selection and spreading of multiresistant bacteria and resistance genes, and *iii)* reduced crop yields and increasing concentrations of pollutants, multiresistant bacteria, and resistance genes in plants as a consequence of concentration effects in the reduced plant biomass. To test these hypotheses, we set up a multi-scale interdisciplinary study at the Mezquital Valley, México. We analyzed the resistant bacteria as well as resistance genes, antibiotics, disinfectants, heavy metals in experimental set-ups considering water quality, dominant soils, and two crops (alfalfa and/or coriander). At the laboratory scale we set-up an incubation experiment, at the greenhouse scale a soil column experiment, and in the field we sampled water, soil and crops irrigated with either treated or untreated wastewater. Additionally, we set up a lysimeter experiment with six 1m deep soil monoliths excavated from long term irrigated fields with untreated wastewater. Since 2019, we have been monitoring the water, nutrient and pollutant balances in response to irrigation water quality change, as well as greenhouse gas emissions and pollutant leachates like nitrates, heavy metals and antibiotics. We will synthesize the main results obtained at each scale and discuss the advantages and limitations of our approach.

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# Development of Environmental Benchmark of Cr(VI) in Soils for the Protection of Groundwater Quality

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**ABSTRACT**

The heavy metal pollutant Cr (VI) has high toxicity and strong mobility, posing a great threat to groundwater safety. The current relevant soil standards often overlook groundwater safety. It is urgent to establish a Cr(VI) soil environmental References value based on groundwater safety in order to provide support for the supervision of contaminated sites. To establish soil environmental benchmark values for Cr(VI) based on the protection of groundwater and tailored to the specific conditions of China, this study addresses the current practice of directly applying a single foreign-derived parameter (e.g., Kd = 19 L/kg). By tracing the complete contaminant migration pathway—"soil-water partitioning, vadose zone attenuation, and groundwater dilution"—a methodological framework was established. This framework integrates soil adsorption, solute transport in the vadose zone (modeled with HYDRUS-1D), and groundwater dilution processes. Systematic adsorption experiments and soil column leaching tests were performed on 12 typical zonal soils across China to determine Cr(VI) solid-liquid distribution coefficients (Kd) and key vadose zone migration parameters. Corresponding regional hydrogeological data were also compiled through comprehensive research. The results show that Kd values for the twelve soils varied widely from 0.25 to 67.75 L/kg. A significant positive correlation ($r = 0.97$) was found between soil Cr(VI) adsorption capacity and free iron oxide content, with clear regional differences observed. The HYDRUS-1D model effectively simulated Cr(VI) migration through different soil types, achieving high goodness-of-fit ($r^2 > 0.98$). Using the Class III groundwater quality standard limit (0.05 mg/L) from GB/T 14848-2017, soil benchmark values for groundwater protection were derived under different conservatism scenarios. Excluding extreme cases in regions like Yunnan and Hainan—where exceptionally high free iron oxide content and thick vadose zones led to anomalously high benchmark values—the derived values generally fell within a reasonable range of 0.39 to 19.61 mg/kg. These results align well with international Cr(VI) benchmarks for groundwater protection. By comparing, we found that if the adsorption attenuation of the air bag tape is ignored, the baseline value will be underestimated by several orders of magnitude, with the maximum difference factor being 466. This would result in the benchmark value being overly conservative. Quantitatively, this confirms that ignoring vadose zone attenuation could lead to substantial and unnecessary remediation costs. This study proposes a benchmark derivation framework supported by localized parameters and emphasizes the vital role of vadose zone attenuation in pollutant migration for benchmark calculations. The framework provides a more scientifically sound basis for managing soil environmental risks to protect groundwater in China. It also offers a methodological foundation for developing regionally differentiated benchmarks in the future.

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# Quantitative Characterization and Prediction Model for the Evolution of Soil Cracks in the Daqing Region

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**ABSTRACT**

This study systematically analyzes the mechanisms by which evaporation rate and the thickness of black soil influence the generation and expansion of soil cracks, with a focus on the physical characteristics of typical soils in the Daqing region. By conducting controlled experiments under varying evaporation rates, soil thicknesses, and initial moisture contents, the study investigates the mass change characteristics during the soil evaporation process. A mathematical model based on mathematical derivation was developed to predict the temporal evolution of soil cracks, enabling a quantitative characterization of the cracking process. The model accurately identifies the critical moments of crack initiation and the key time points when crack expansion stabilizes.

The results indicate that both the evaporation rate and soil thickness significantly affect the crack formation time and expansion rate. A higher evaporation rate accelerates soil moisture loss, leading to earlier crack formation and a marked increase in the rate of expansion. Conversely, a greater soil thickness has a delaying effect on crack initiation and plays an important regulatory role in the crack evolution process and its final morphology. Moreover, a significant interaction exists between the evaporation rate and soil thickness, which jointly determines the timing and development characteristics of soil cracks.

These findings provide scientific support for regional soil moisture management, agricultural irrigation optimization, and drought-related disaster early warning systems. Additionally, the study offers an effective technical pathway and theoretical tools for improving agricultural sustainability and addressing soil structure degradation in the context of climate change.

This translation is aligned with the formal language and style typical of scientific publications, suitable for submission to high-impact journals.

**Keywords:** Soil Cracks; Evaporation Rate; Soil Thickness; Crack Evolution Model

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# A Hybrid SWAT-LSTM Framework for Daily Sediment Load Prediction in the Data-Scarce Songhua River Basin, Northeast China

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**ABSTRACT**

The Songhua River Basin in Northeast China is a major agricultural region with extensive streamflow records but very limited sediment monitoring, which hinders effective water resource management and soil conservation. This study presents a hybrid modeling approach that integrates the process-based Soil and Water Assessment Tool (SWAT) with a Long Short-Term Memory (LSTM) deep learning network to simulate daily sediment load in data-scarce catchments. The LSTM was trained in one gauged sub-basin to correct biases in the SWAT sediment simulations, and the trained model was transferred to 17 neighboring sub-basins lacking sediment observations. The hybrid SWAT-LSTM model dramatically improved performance at the training site, raising the Kling-Gupta Efficiency (KGE) from 0.20 to 0.79 compared to SWAT alone. When applied to ungauged basins without local sediment data, the framework produced reliable predictions at most sites (12 out of 17 had KGE > 0.4). Model performance was strongly dependent on the accuracy of the underlying streamflow simulation and was non-linearly influenced by catchment area. These findings demonstrate a viable solution for estimating sediment yields in ungauged basins and provide insight into the factors affecting hybrid model transferability in regional sediment load prediction.

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# A physics-guided representation embedding framework for transferable estimation of soil water content and bulk density in Mollisols using TDR

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## ABSTRACT

In Mollisols, pronounced polarization mechanisms inducing strong relaxation and dispersion lead to systematic distortion of time-domain reflectometry (TDR) waveforms and limit the applicability of conventional TDR analysis methods based on travel-time picking methods and waveform inversion. A physics-guided representation embedding framework with transfer learning was proposed. The framework encodes simulated TDR waveforms using multi-scale response templates to learn low-dimensional embeddings that are robust to characterize and partially decouple electromagnetic responses. Soil water content and bulk density are jointly estimated in the embedding space using support vector regression. Transfer from the simulation parameter domain to the field domain is achieved with only a limited number of measured samples, enabling robust estimation of soil properties in Mollisols from TDR waveforms. The framework was initially trained on about two thousand simulated waveforms and validated through simulation-to-field transfer using 35 measured waveforms. Under the setting, coefficients of determination ($R^2$) for soil water content and bulk density reach 0.91 and 0.70, respectively, with corresponding root mean square errors (RMSE) of 0.01 $m^3$ $m^{-3}$ and 0.07 g $cm^{-3}$. The results demonstrate that the proposed framework provides a robust strategy for retrieving soil physical properties from TDR measurements under limited field calibration.

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# Probabilistic and Entropy Models of Soil Properties for Contemporary Processes Assessment

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**ABSTRACT**

Heterogeneity, variability, and fluctuations in soil properties at all levels of soil organization are major features of soils, as the latter are open dynamic complex systems that evolve over time. This means that the quantitative expression of properties in the soil profile can change gradually, while both the central characteristics and the variability itself change. Our studies have shown that the patterns of variability of even stable soil properties, for example granulometric composition, which are used in models parameters, can change over time. This must be taken into account in mathematical modeling of dynamic soil processes, especially if model calculations are made for large areas and for a long time. Assessment of changes of soil properties at the scale of agricultural fields is important because it allows drawing conclusions about the contemporary processes happening in soils caused by anthropogenic influence and climate changes. We consider them as the contemporary evolution of soil (CES), namely process of changes of soil conditions with time intervals from ten to hundred years. When carrying out spatial soil monitoring, points of approbation in space don't coincide at different time, so it is necessary to use probabilistic models for assessment of states and changes of soils. Therefore we have offered to use probabilistic and information indicators for assessment of condition of soils and their changes. The characteristic of variability of a system property is its probability distribution function within the studied object. Therefore the model of a condition of the soil represents the set of pdf of n soil properties in its k horizons. We have determined the best mathematical functions of pdf of soil properties by applying special statistical procedure to datasets of legacy data. For scalar characterization of the variability of the soil condition the values of the information (statistical) entropy of the soil properties were used. For assessment of changes of soils were used the values of information divergence of soil properties and an increment of their entropy. The entered characteristics allow general scalar estimating extent of influence for the soil forming factors and anthropogenic impacts on probabilistic structure of values of soil properties and its stability. The case studies have been conducted in the big territory at the south of Western Siberia. It has been shown that CES occurs under the anthropogenic influences (long-term plowing, strip agriculture, irrigation) and natural processes caused by climatic trend of warming and by cycles on moistening. It is revealed the changes of probabilistic structure of values of properties of the soil in their horizons. In fact, the received models and estimates are probability and entropy standards of condition of soils which should be used for comparison with the past, current and future native or modelled results in the explored and neighboring territories.

**Key words:** soil, properties, variability, processes, evolution

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# Advancing Daisy's denitrification function to improve predictions of nitrous oxide emissions from agricultural soils

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**ABSTRACT**

Countries are increasingly striving for a Tier 3 approach when reporting greenhouse gas emissions (GHG) caused by their agricultural sector. This approach requires the use of sophisticated models that produce reliable estimates of these emissions. In this context, nitrous oxide ($N_2O$) – a major GHG emitted from agricultural soils – poses a particular challenge as its production in soil is erratic and results from the complex interplay between physical, chemical and biological soil processes.

*Daisy* is a process-based agroecological model, which was developed for simulating water, carbon and, in particular, nitrogen fluxes at the field scale. Yet, *Daisy* still maintains a relatively simple and poorly tested description of denitrification, which is one of the major pathways of $N_2O$ production in temperate agricultural soils. Here, the testing and advancement of *Daisy's* denitrification function is presented, with the aim of improving its ability to predict $N_2O$ emissions.

We capitalized on recently gathered datasets from across Denmark, which cover a range of soil types, crop rotations (including cover crops), and varying supplies of mineral and organic fertilizers. First, crop and soil hydraulic parameters were calibrated against an array of field and laboratory measurements, supported by soil profile descriptions. Subsequently, the fraction of nitrified ammonium emitted as $N_2O$ was estimated from the literature and refined during the calibration process of the denitrification function. Finally, the denitrification function was addressed using iterative cycles of calibration, output analysis and function adjustments. For this purpose, a new *Daisy* tool for numerical parameter optimization was used, allowing for sequential and covariance matrix adaptation evolution strategy (CMA-ES) optimization.

*Daisy's* original denitrification function performed well during intermediate-flux periods, while $N_2O$ emissions were overestimated during low-flux periods when soil mineral nitrogen contents were low. This issue was addressed by exploring the use of nitrate limitation functions of other denitrification models and by taking into account the findings of recent empirical studies. Furthermore, *Daisy* underestimated $N_2O$ emissions after slurry application, probably due to the creation of anaerobic hotspots and the increase in water retention induced by the slurry, which the model cannot account for. In this context, we suggest the possibility of different parameterizations for mineral and organic fertilizers and stress the importance of slurry parameterization. Other aspects discussed in this work are the need to consider the whole nitrogen budget during calibration, and how literature data can help constrain the parameter space during optimization. Lastly, *Daisy's* potential for $N_2O$ emission predictions is highlighted, not the least due to its physically based description of soil water dynamics and root water uptake.

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# The impact of agricultural land use on soil hydraulic properties and hydrological functioning across the lowlands of England and Wales

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**ABSTRACT**

This study evaluates the impact of agricultural land use choice (e.g. crops versus permanent grassland) on soil hydrological functioning, by analysing pore-size distributions (PSD) and hydraulic properties together with basic soil properties, across lowland soils in England and Wales. Informed by these analyses, hydrological modelling was employed, using two models (HYDRUS-1D and SWAP), to assess the effects of land use (change) on soil water balance fluxes and stores. This study analysed top- and subsoil physical data from UK NATMAP database for sixteen major soil series in England and Wales, varying in texture and drainage conditions, as well as corresponding basic soil properties (e.g. texture, soil organic carbon and pH). The results indicate that land use (change) significantly influences soil structure, PSD and hydraulic characteristics. Largely via increased biological activity and soil organic matter content, grassland promotes the development of increased total pore volume, with the largest increases in the macropore range, and enhances soil hydraulic functioning. Permanent grassland also has increased air capacity, plant-available water capacity, and saturated hydraulic conductivity, compared to cropped soils. Compared to bare arable land (AR) soils, bare permanent grassland (PG) soils generally contain more water due to their greater water retention capacity, but higher evaporation rates associated with these soils leads to reduced deep drainage. Similarly, relative to winter wheat on AR, grass on PG tend to maintain higher soil moisture levels; however, increased water losses via evapotranspiration and canopy interception under grass on PG result in reduced deep drainage.

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# Differentiable Hybrid Modeling for Data-Driven Discovery of Hidden Processes in Soil Water Retention

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**ABSTRACT**

A century ago, soil physicists had neither the amount of data nor the scientific computing methods available today. As a result, they had to make (over) simplifying assumptions about many intermediate soil processes that are complex and largely unobservable (e.g., assuming certain pore shapes, equilibrium conditions, or specific forms for soil hydraulic properties). While these simplifications enable tractable formulations, they are shaped by the modeler's view of the system that may bias the true representation of soil processes. At the same time, the increasing availability of high-quality data offers an opportunity to both improve the predictive power of existing models and gain new fundamental soil physics insights. Here, we propose differentiable hybrid modeling (DHM) that combines analytical formulations with flexible, data-driven components to learn uncertain parts directly from data. A key enabler is end-to-end differentiability via automatic differentiation, which allows the entire model, including physical and neural components, to be optimized jointly by minimizing a downstream loss function. We apply this approach to the challenge of partitioning the soil water retention curve (SWRC) into capillary and adsorbed water components. The hybrid model, trained on 483 undisturbed soils from Central Europe, produces smooth and physically consistent SWRC curves and automatically discovers the capillary and adsorptive branches of the curve. Notably, the model reveals a distinctly nonlinear transition between capillary and adsorbed domains, challenging the linear assumptions invoked in previous studies. The methodology introduced here provides a blueprint for learning other soil processes where high-quality datasets are available but mechanistic understanding is incomplete.

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# Modeling On-Farm Spatial Variability of Crop Yield

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**ABSTRACT**

Soils in Western Kentucky that are used for intensive agricultural production are developed on Karst topography. Therefore, they exhibit substantial spatial variability and temporal dynamics of above- and belowground processes that affect crop growth. Managing water and nutrients in these soils and describing crop yield variability through modeling approaches are challenging tasks. The objective of this study is to analyze factors causing spatial crop yield variability and to describe crop yield variability with a deterministic, physically based model and a stochastic approach. In this study, the Root Zone Water Quality Model RZWQM2 which is a deterministic process-based model, and the stochastic state-space approach are used for modeling spatial variability of crop yields. Soil textural data input and parameterization of hydrological model input parameters are studied at different spatial resolutions in the RZWQM2. In the state-space model, relevant site information including remote sensing and topographic state variables is identified for predicting spatial variability of crop yields. The soil type at this 47-ha-field site of this study is a Crider silt loam with an elevation range between 132 and 155 m. Soil textural composition was quantified at a 50-m-grid in five layers from 0 to 100 cm soil depth. Measured soil textural information and the estimation of soil hydraulic properties using the Brooks-Corey equation is compared with the Soil Survey Geographic Database (SSURGO) from the Natural Resources Conservation Service (NRCS) in RZWQM2 simulations. UAV- and Satellite-based remotely sensed information of NDVI and topographic indices based on the Kentucky LiDAR map (Kentucky Government) are used in the state-space model for describing yield variation. Results are shown for a two-year crop rotation.

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# Coupling soil biogeochemical processes and structural dynamics in a pore-scale model for an advanced understanding of organic carbon and nitrogen turnover

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**ABSTRACT**

Soil organic matter (SOM) turnover plays a major role in the global carbon cycle, while also influencing soil health and fertility.

Accurate modeling of SOM dynamics requires a comprehensive understanding of the complex interplay between biogeochemical and physical processes occurring at small spatial scales.
The availability of carbon (C) and nitrogen (N) resources governs microbial growth, while microbial dynamics, in turn, shape the distribution of C and N within soils. (Dis-)Aggregation processes influence the persistence and degradation of organic carbon, as physical protection of organic matter within soil aggregates promotes carbon storage.

We present a mechanistic, spatially explicit pore-scale model that couples microbial dynamics with evolving soil structure. The model describes microbial growth and necromass formation driven by the enzymatic degradation of particulate organic matter (POM), microbial necromass, and root exudates, explicitly accounting for their C/N ratios, which influence respiration and N cycling [1]. A cellular automaton approach represents soil structure dynamics, including aggregation, occlusion, and the formation of organo-mineral associations that stabilize organic matter [2].

Our simulations based on images of soil aggregates and parameters derived from rhizosphere experiments explore how (i) soil structural heterogeneity and connectivity, (ii) N availability, and (iii) organic matter quality shape microbial activity, soil organic carbon (SOC) stabilization, and C use efficiency.
The simulations reveal and quantify how dynamic pore connectivity controls substrate accessibility and generates transient microscale hot and cold spots of microbial activity. Limited N availability constrains microbial growth, whereas the input of root exudates with favorable C/N ratios promotes biomass formation and increases CUE. The resulting C respiration is consistent with laboratory experiments. Microbial necromass emerges as a long-term SOC pool that becomes physically protected within the evolving soil structure.

By explicitly coupling microbial and structural dynamics, our framework provides valuable insights how pore-scale processes influence soil C and N cycling and long-term soil carbon storage under changing environmental conditions.

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# Fusing ERA5-Land and SMAP L4 for an Improved Global Soil Moisture Product

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**ABSTRACT**

Accurate, high-resolution soil moisture data are critical for hydrological modeling, climate studies, and ecosystem management. Unfortunately, current existing global products suffer from inconsistencies, coverage gaps, and biases. In this study, we evaluated the surface layers of three widely used soil moisture products, including ERA5-Land, ESA-CCI (v09.1 Combined), and SMAP L4 with resolutions ranging from 0.1° to 0.25°, against in situ measurements from 1,615 stations across five networks, including ISMN, CMA, Cemaden, COSMOS-Europe, and SONTE-China. The in situ dataset, to our knowledge, represents the most extensive global soil moisture compilation to date. It is found that ERA5-Land exhibits high correlation between measured and predicted soil moisture but the data also shows significant bias. SMAP L4 provides the highest accuracy, exhibiting low bias and root mean square error (RMSE), but is limited by its temporal coverage from 2015 to the present. To address these gaps, we developed an adjusted ERA5-Land dataset by fusing ERA5-Land and SMAP L4 using a mean-variance rescaling method optimized for long time-series alignment, which enhanced the spatiotemporal coverage and reduced bias. Validation against in situ measurements demonstrates a reduction in RMSE of 24.6% and an improvement in normalized Nash-Sutcliffe Efficiency (NNSE) of 30.6% compared to the original ERA5-Land products. The adjusted ERA5-Land dataset, which is publicly available, can be used as benchmark for future research and support drought monitoring, weather prediction, and water resource management, contributing to global climate resilience across diverse ecosystems.

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# Quantitative Analysis of Pore Scale Factors Effecting Permeability in Porous Media

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**ABSTRACT**

Porous media, such as rocks and soils, are essential for addressing scientific and engineering challenges in hydrology, materials science, and petroleum engineering. Fluid flow in these media originates at the pore scale, where complex geometries dictate macroscopic permeability, a property highly sensitive to factors like porosity, pore-throat sizes, tortuosity, and connectivity. Traditional models, such as the Kozeny-Carman equation, often fail to capture this heterogeneity, leading to inaccurate predictions. Advances in X-ray computed tomography and computational methods, including Lattice Boltzmann simulations and particle packing, enable detailed pore-scale analysis.

The research investigates pore-scale influences on permeability in porous media through computational simulations and imaging data analysis. We explore how material properties affect pore structures and fluid dynamics, advance methodologies for defining representative volumes considering microstructural aspects, and formulate predictive models using data-driven techniques to estimate permeability from fundamental parameters.

The derived model enhances accuracy for diverse heterogeneous systems, bridging simulated ideals with natural geological contexts and surpassing conventional empirical methods.

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# Improving Digital Soil Hydraulic Characterization: A Workflow for Enforcing Periodic Boundary Conditions on Tomographic Soil 3D Images

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**ABSTRACT**

Predictive modeling of water flow in soils relies on accurate knowledge of the saturated hydraulic conductivity tensor (K). While 3D X-ray microtomography and pore-scale modeling offer a direct way to estimate K from soil structure, a key technical challenge is the creation of a representative digital domain with consistent boundary conditions. Conventional simulations using closed-wall boundaries introduce artificial flow restrictions, contradicting the natural, extensive conditions of a soil sample [1].

This study presents a novel, algorithmic workflow for the generation of seamless periodic boundary conditions for 3D images of complex natural soils. The core innovation is a method that does not alter the original internal structure of the segmented 3D image. Instead, it grows an external layer of porous material whose statistical morphology and transport properties are indistinguishable from the original core. This is achieved by a sophisticated combination of stochastic reconstruction algorithms based on multipoint statistics and correlation functions [2], ensuring the new boundary zone is a faithful continuation of the sample's pore space geometry.

The algorithm specifically tackles challenges inherent to soil porous media, such as complex pore connectivity, presence of isolated voids, and the irregular geometry of solid aggregates. We rigorously tested the effectiveness of the generated PBCs using Stokes flow solver [3], comparing flow fields and resulting K-tensors against simulations with conventional closed boundaries.

The presentation will showcase the algorithm's application on tomographic images of contrasting anisotropic soil samples. The results demonstrate that our method enables physically correct pore-scale modeling with periodic boundaries, effectively representing an infinite medium, as opposed to the unrealistic confined system imposed by closed walls. This computational tool bridges the gap between high-resolution imaging and reliable hydrodynamic characterization, advancing the methodology of digital soil physics and contributing to more robust predictions of soil water dynamics.

**Acknowledgments**

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# Multi-scale simulations of soil transport properties with dynamic soil structure: combination of molecular, micro and continuum approaches

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**ABSTRACT**

While continuum scale is indispensable due to its low computational cost, the latter benefit is not without its high toll. Major physical properties and processes can be explained only on the pore-scale, as homogenization leads to severe information loss. In their turn, pore-scale models operate using parameters that can be effectively obtained based on molecular scale simulations (e.g., interfacial tension, transport properties of sub-micron pores [1], wetting properties [2]). In this contribution we shall discuss a truly multi-scale paradigm to describe soil processes involving transport properties and soil structure dynamics.

Soil structure defines its hydraulic properties, but, in turn, depends on boundary conditions such as water content. Thus, to correctly represent such properties on all necessary scales and, finally, properly parameterize the continuum scale model, one needs to explore at least the following Russian nesting doll:

1) Molecular scale provides fluid properties, fluid-solid interaction parameters and predict how moisture conditions affect swelling-shrinkage;
2) Microscale operates on classical hydrodynamics and can assess saturated and unsaturated flow properties.
3) Continuum scale is parameterized using properties obtained from microscale simulations or measurements, and heavily relies on representativity concept [3].

The presentation will provide numerous evidences in favor of our approach and showcases of applications on all aforementioned scales. The results suggest that without involving structural soil analysis [4] and modelling on all relevant scales one simply can not upscale to continuum without introducing numerous errors. Moreover, we shall provide a number of open-source solutions to address some of the issues raised in contribution.

**Acknowledgments**

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# A New Nonlinear Method for Simulating Nitrogen Pollutant Transport in Farmland

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**ABSTRACT**

The control of agricultural non-point source pollution is a crucial component of ecological and environmental protection. Inappropriate chemical fertilizer application and land management policies can lead to unabsorbed harmful substances such as nitrates in fertilizers seeping into groundwater through percolation, causing environmental damage. Therefore, it is essential to develop accurate mathematical models to simulate the nitrogen transport mechanisms in the plow layer. Based on a system of nonlinear partial differential equations, the aim of this work was to quantify the diffusion coefficients of black soils through indoor soil column experiments and numerical simulations. The control experiment consisted of three typical soil types in the black soil region, two soil moisture treatments, two fertilization rate treatments, a blank control group, and was conducted with three replications. The results indicate that the vertical migration of nitrate nitrogen primarily occurs in the early stage of percolation, moving deeply into the soil with water flow and posing a high risk of water pollution. In contrast, the vertical migration of ammonium nitrogen mainly takes place in the late stage of percolation, and it is gradually immobilized and consumed by the soil. The nonlinear equation system based on Newton's seepage equation can effectively simulate the nitrogen transport processes in black soil regions. Furthermore, parameter sets tailored to different textured black soils are provided, enabling precise simulation of agricultural nitrogen transport. This study offers an effective method for predicting agricultural non-point source pollution.

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# Predicting the Impacts of Metal Nanoparticles on Soil Properties: A Machine-Learning–Based Study of Soil Health Dynamics

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**ABSTRACT**

Metal nanoparticles (MNPs) hold considerable promise for precision and sustainable agriculture. However, the interaction mechanisms between different MNPs and soil physicochemical properties, particularly their effects on integrated soil health metrics, remain poorly understood. In this study, we employed four interpretable machine learning algorithms, including XGBoost, Random Forest (RF), Gradient Boosting Decision Trees (GBDT), and Support Vector Machine (SVM), to systematically analyze the interactive influences of seven soil physicochemical properties, three MNP characteristics, and three external environmental factors on seven soil health indicators.

Taking a global perspective, we predicted the effects of MNPs on soil health indicators across 12 USDA soil taxonomy classes (Figure 1). Our results indicate that MNP impacts are highly dependent on soil properties and vary markedly among soil types. For example, Entisols, which exhibit low soil water holding capacity (SWHC) and low soil organic matter (SOM), showed pronounced sensitivity in pH to MNP exposure: the magnitude of pH change ranged from 2.6% to 11.5%, substantially larger than in other soil types (pH change range from −2% to 4%). In contrast, Mollisols and Inceptisols, which are important agricultural soils in regions such as Europe, the United States, Canada, and China, exhibited greater sensitivity of microbial biomass and biodiversity (Shannon index) to prolonged MNP exposure. Over a 365-day exposure period, microbial biomass in Mollisols and Inceptisols declined by 60% to 268%, whereas under short-term exposure (30 days) the decline was only 4% to 20%.

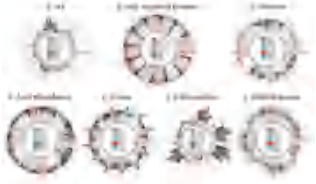


Figure 1. Changes in pH (a), soil microbial biomass (b), Shannon diversity index (c), acid phosphatase (d), urease (e), β-glucosidase (f), and dehydrogenase (g) across different soil types after 30, 180, and 365 days of exposure to metal nanoparticles (MNPs).

We further assessed potential risks of MNPs to soil health at the global scale and identified high-risk regions and soil types (Table 1). For instance, Entisols and Oxisols in tropical and subtropical regions, owing to their low SWHC and SOM, are particularly sensitive to pH alterations, which can substantially affect nutrient availability and ecosystem productivity. Aridisols occurring in arid regions such as the western United States, the Middle East, and Central Asia showed pronounced impacts on microbial diversity and enzyme activities, reflecting the vulnerability of their microbial communities. By contrast, Mollisols and Inceptisols characterized by relatively high SOM and soil clay content (SC) demonstrate greater stability in pH and microbial diversity; nevertheless, long-term MNP exposure may lead to declines in microbial biomass and enzyme activities, with consequent impairments to nutrient cycling and carbon sequestration capacity.



Table 1. Sensitivity analysis of seven soil health indicators to variations in MNP particle size (NPS), concentration (NPC), and exposure duration (ED) under MNP exposure, and the distribution of high-risk countries and soil types. Subscripted letters in parentheses denote regions where sensitivity value distributions differ from the global pattern. [a] NPC sensitivity > 800 mg·kg$^{-1}$ in Russia, Canada, the Indian subcontinent, and Southeast Asian islands; [b] NPS sensitivity = 50–70 nm in North Africa, South Africa, the Arabian Peninsula, and Australia; [c] Under $Fe_3O_4$-NPs, $CeO_2$-NPs, and ZnO-NPs exposure, NPC sensitivity > 600 mg·kg$^{-1}$ in Russia, Canada, Brazil, and South Africa; [d] Under $Fe_3O_4$-NPs and $TiO_2$-NPs exposure, NPS sensitivity > 40 nm in North Africa and South Africa; [e] Under $TiO_2$-NPs and ZnO-NPs exposure, NPC sensitivity > 500 mg·kg$^{-1}$ in Mollisols; [f] NPS sensitivity < 30 nm in Ultisols; [g] NPC sensitivity > 700 mg·kg$^{-1}$ in Entisols; [h] ED sensitivity in Entisols = 120–130 days; [i] NPS sensitivity > 20 nm in Gelisols and Oxisols.

Our observations reveal clear differences between the short-term and long-term effects of MNP exposure. Because the existing literature predominantly focuses on short-term impacts, current assessments may underestimate the true risks MNPs pose to soil health and ecosystem functioning. The findings underscore the necessity of incorporating specific soil physicochemical properties and long-term exposure scenarios in MNP risk assessments. Moreover, this study highlights practical implications for sustainable agriculture and land management. In high-risk areas, mitigation measures such as cover cropping, application of organic amendments, and conservation tillage can be implemented to increase SOM and SWHC and thereby alleviate adverse MNP effects. In fertile agricultural soils, monitoring systems for microbial biomass and enzyme activities should be established to inform adaptive management strategies, for example, crop rotation and reduced reliance on chemical inputs.

By producing global predictions across diverse soil types, this study evaluates potential risks of MNPs to soil health, identifies high-risk regions and countries, and provides data support for targeted follow-up analyses. These results offer a theoretical and data-driven basis for scientifically informed environmental management and sustainable agricultural practices.

**Acknowledgments**

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# Simulating Soil-Plant-Climate Interactions and Greenhouse Gas Exchange in Boreal Grasslands Using the DNDC Model

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**ABSTRACT**

With global warming, arable land in boreal regions is tending to expand into high latitude regions in the northern hemisphere. This entails certain risks; such that inappropriate management could result in previously stable carbon sinks becoming sources. Agroecological models are an important tool for assessing the sustainability of long-term management, yet applications of such models in boreal zones are scarce. We collated eddy-covariance, soil climate and biomass data to evaluate the simulation of GHG emissions from grassland in eastern Finland using the process-based model DNDC. We simulated gross primary production (GPP), net ecosystem exchange (NEE) and ecosystem respiration (Reco) with fair performance. Soil climate, soil temperature and soil moisture at 5 cm were excellent, and soil moisture at 20 cm was good. However, the model overestimated NEE and Reco following crop termination and tillage events. These results indicate that DNDC can satisfactorily simulate GHG fluxes in a boreal grassland setting, but further work is needed, particularly in simulated second biomass cuts, the (>20 cm) soil layers and model response to management transitions between crop types, cultivation, and land use change.

**Acknowledgments**

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# Process-based modelling of river sediment composition incorporating pedogenetic processes at the catchment scale: the Sendaigawa River basin, Japan

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**ABSTRACT**

In recent years, climate change has altered rainfall patterns and intensified precipitation events, leading to situations in which conventional statistical approaches for predicting soil erosion rates and assessing associated hazards are becoming increasingly inadequate. Accurately identifying locations that are prone to sediment-related disasters in advance through the development of more mechanism-based models has therefore become an urgent challenge.

The authors have conducted a series of studies aimed at assessing sediment-related disaster risk at the watershed scale by quantitatively characterizing both the quantity and quality of river sediments (RS) and suspended particulate matter (SPM). Previous studies demonstrated that the elemental composition of RS reflects upstream geology, weathering, and pedogenetic processes, whereas SPM reflects not only these soil-related factors but also contemporaneous meteorological and hydrological conditions, such as changes in river discharge. Furthermore, when RS was fractionated by particle size—gravel (R), coarse sand (CS), fine sand (FS), silt (S), and clay (C)—similarities in elemental composition, particularly in silica content, were detected within specific sub-catchments.

However, an integrated modelling framework that combines soil formation processes, meteorological conditions, and hydrologically driven material transport within the watershed has not yet been established. Therefore, the objective of this study is to develop a climate-driven soil component export model that quantitatively integrates these relationships.

Sampling was conducted at 11 sites within the Sendaigawa River basin, Tottori Prefecture, Japan, consistent with previous studies, on 13 October 2023, 5 August 2024, and 12 November 2024. SPM was collected by filtering 1 L of river water through a 0.45 μm membrane filter. RS samples were fractionated by particle size using sieving and pipette methods into gravel (R), coarse sand (CS), fine sand (FS), silt (S), and clay (C). The elemental composition of all samples was measured using X-ray fluorescence (XRF) spectrometry. In addition, major ion compositions of the filtered river water were determined using high-speed ion chromatography.

The model consists of two main components: a hydrological module that predicts river discharge from precipitation distributions based on simplified hydrological assumptions, and a sediment–water quality module that predicts the export processes of RS and SPM using geological and soil distribution data. The former was validated using observed discharge data provided by the Ministry of Land, Infrastructure, Transport and Tourism of Japan, while the latter was validated using measured elemental and ionic compositions of each fraction obtained in this study. Detailed results of the model validation will be presented and discussed during the presentation.

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# Evaluating Conditioned Probabilistic Subsampling for the Validation of 3D Regional Subsurface Models using Legacy Data

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**ABSTRACT**

With the increasing availability of soil data in various forms it is more common to develop models using only legacy data. While model development is ideally preceded by sampling design aligned with the desired outcome, pre-existing data can partially fulfil requirements and allow for larger-scale modelling such as regional subsurface characterisation. The resulting models can also serve as tools to identify information gaps and model limitations. Interpreted soil borehole profiles, for example, form the basis of multidimensional subsurface models. The availability of data in a certain study area, however, can still be relatively low given the desired resolution or precision of the model. A deliberate decision on sampling existing datasets in general, and creating subsamples for model calibration and validation in particular, is therefore essential during performance assessment of different models. While cross-validation techniques are commonly applied to maximize data utility, their application in spatial modelling yields overoptimistic performance estimates with high variance, particularly when data are clustered. Probabilistic-based sampling is known to tackle bias, but its effectiveness remains poorly understood for spatially sparse and clustered legacy data.

In this research, the effect of subsampling methods on the validation of spatial interpolation techniques is assessed in a study region with legacy boreholes spanning over a century. Simple random subsampling is compared to conditioned Latin hypercube subsampling of boreholes in terms of true model performance. The conditioning 2D legacy characteristics consisted of age, coordinates and target feature statistics. We evaluated the impact of subsample size and anisotropic autocorrelation structure using the same 2D legacy configuration populated with three different 3D target features: two spatially continuous synthetic distributions and one heterogeneous field-observed peat content distribution. Variance reduction was observed only in the spatially heterogeneous case when the validation subsample size was sufficient (35%) to support conditioning that included the cumulative peat content within a borehole. This demonstrates that conditioned probabilistic subsampling can be more robust than other methods for the validation of models derived from legacy data. Our findings also provide insights into different sources of variance within validation results.

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# Generalizability optimization of soil thermal conductivity models: unified estimation of dry- and saturated-soil thermal conductivity

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**ABSTRACT**

Soil thermal conductivity (λ, W $m^{-1}$ $K^{-1}$) is a fundamental physical parameter governing coupled water and heat transport in soils, with broad relevance to thermal energy engineering, soil physics and agrometeorology. However, widely used empirical λ prediction models are often limited in their applicability across soil textures, bulk densities and water content ranges. A substantial fraction of the prediction error arises from uncertainties in estimating dry soil thermal conductivity ($\lambda_{dry}$) and saturated soil thermal conductivity ($\lambda_{sat}$). In this study, we optimized the calculation methods of $\lambda_{dry}$ and $\lambda_{sat}$ and incorporated a unified parameterization into five commonly used empirical models to improve their transferability. The validation results based on 213 literature-derived datasets and 175 measured datasets, spanning soil textures from sand to clay, bulk densities of 1.1–1.7 g $cm^{-3}$, and a wide range of total water contents. The improved models consistently enhanced predictive performance. Compared with the original models (RMSE 0.183–0.277; SD 0.458–0.601; $R^2$ 0.893–0.946), the improved models achieved RMSE 0.128–0.166, SD 0.335–0.435, and $R^2$ 0.947–0.959 across all conditions. The contribution of $\lambda_{sat}$ in the two parameters to the accurate prediction of λ is higher than that of $\lambda_{dry}$, and the $R^2$ is ≥ 0.88. Overall, the unified estimation of $\lambda_{dry}$ and $\lambda_{sat}$ reduces the prediction bias without modifying the main structure of the existing models, thereby improving their general applicability across diverse soil scenarios.

**Keywords:** Soil thermal conductivity; Model optimization; Textures; Water contents; Bulk densities

# SoilData: A MapBiomas Initiative for Soil Data Rescue, Curation, and Open Science in Brazil

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**ABSTRACT**

The historical fragmentation of Brazilian soil data—often confined to non-digital legacy reports or institutional silos—has long hindered large-scale environmental modeling. This study presents the SoilData repository (soildata.mapbiomas.org), a centralized open-science infrastructure designed to safeguard, standardize, and disseminate soil information. Developed and managed as an initiative of the MapBiomas network, SoilData is a member of the National Consortium for Open Science (CoNCienciA). This partnership allows the repository to leverage international standards for data governance, including the attribution of Digital Object Identifiers (DOIs) via DataCite to ensure that datasets are citable and discoverable in global indexes.

The SoilData architecture is built upon a four-stage technical workflow: (1) inventory and acquisition, which combines active rescue of legacy data (digitizing theses, reports, and articles) with voluntary deposits from independent researchers; (2) structuring and standardization, where raw data is transposed into a machine-readable format and subjected to semantic harmonization using standardized vocabularies and unit conversions; (3) quality control, involving automated logical checks for physical consistency (e.g., mass balance of granulometric fractions) and spatial verification to correct georeferencing errors; and (4) publication and safeguard, ensuring long-term preservation and data traceability under a Creative Commons licenses.

The repository currently (Dec. 2025) hosts over 298 datasets, approximately 19,409 points (of which 16,515 are geoReferencesd) and 61,242 samples. When standardized and harmonized, this yields more than 15,000 geoReferencesd points and 45,000 samples of analysis ready soil data (ARD). This ARD dataset provides information on organic carbon content, bulk density, and granulometry up to 100 cm depth. Furthermore, the repository has expanded its scope through specialized thematic groups, such as the Soil Erosion Data Community, to address emerging environmental priorities. By providing a robust, transparent, and citable foundation for pedological research, SoilData serves as a vital tool for democratizing soil information in Brazil and supporting sustainable land management and climate adaptation.

**Keywords:** Data repository, Analysis ready data, Organic carbon, Bulk density, Granulometry

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# Estimation of Soil Temperature at Depth Using Time Series of Satellite Imagery

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**ABSTRACT**

Soil temperature and its temporal and spatial variations constitute one of the most critical factors influencing not only mass and energy exchange in the soil, but also the magnitude and direction of all physical processes within the soil, either directly or indirectly. Given the practical challenges associated with in-situ measurement of soil temperature at depth, this study utilized land surface temperature (LST) derived from the MODIS sensor, which provides four observations per day. These data were subsequently modeled to generate hourly time series. The percentage of missing data in these images was estimated both temporally and spatially. The application of the HANTS (Harmonic Analysis of Time Series) algorithm for reconstructing MODIS LST time series demonstrated that separate reconstruction of daytime and nighttime images yields higher accuracy compared to combined day-night series. To further improve reconstruction accuracy, the Multivariate Singular Spectrum Analysis (MSSA) algorithm was also employed, and different window lengths were evaluated. Ultimately, a window length of 60 days was selected, achieving the highest accuracy with an RMSE of 1.4 °C. In order to generate hourly-resolution LST time series using only four daily MODIS LST observations per day, six different diurnal temperature cycle (DTC) models were compared. These models incorporated critical parameters such as sunrise and sunset times, day length, and other astronomical variables for each day. Cross-validation results indicated that the DTC models ranked in descending order of accuracy as follows: DTC1 > DTC6 > DTC5 > DTC4 > DTC3 > DTC2. Soil heat flux images derived from MODIS were reconstructed using MSSA and subsequently modeled to hourly resolution. Soil thermal admittance was estimated using the ratio of the amplitude of soil heat flux to surface temperature at different frequencies. Deep learning techniques were then applied to the derived thermal admittance images to obtain soil thermal diffusivity and damping depth images. Analysis of the MODIS-derived damping depth images revealed that damping depth increases with increasing soil depth. Hourly soil temperature at depth was estimated using the sinusoidal analytical solution, based on MODIS-derived surface temperature time series. Validation results showed that the highest accuracy was achieved at 5 cm depth, while the lowest accuracy occurred at 20 cm depth. Except for the 5 cm depth (where the lowest accuracy was observed at 12:30), the lowest accuracy at all other depths was consistently found at 06:30 local time. Monthly average soil temperature variations from the surface to deeper layers were investigated throughout the year. Finally, a novel methodology is proposed for estimating soil temperature at depths of 5, 10, and 20 cm using MODIS imagery. This approach explicitly accounts for day length variation, sunrise and sunset times, thermal damping depth, and phase shift. Identifying and analyzing subsurface thermal behavior is essential for risk management and proper infrastructure planning The subsequent phase of the research is designed to examine underground heat distribution patterns and to identify subsurface heat islands.

**Keywords:** Soil heat flux, daily cycle of land surface temperature, thermal inertia, soil thermal acceptance

# Predicting soil and macropore hydraulic properties: combination of direct simulations and machine learning

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**ABSTRACT**

Predicting hydraulic properties is an important task necessary in building multi-scale models for various soil processes. Pore-scale simulations provide a fresh look at this task as they can mitigate numerous experimental problems or apply more realistic boundary conditions [1]. Direct simulations on 3D images of porous media are computationally heavy. With the advent of modern statistical methods in the form of machine learning techniques, one can predict hydraulic properties quite cheaply by leveraging data from direct simulations [2]. There different approaches to the task, for example, it is possible to extract features from the whole soil structure [3]. However, one can apply the technique separately to each pore – this way we can use pore-networks to perform simulations in a more robust way, or to combine multi-scale soil structural features- regular pores and macropores, that are usually addressed separately within modelling domains.

In this contribution, we shall use the latter approach and present results of training a model on different types of pore elements, including macropores. As input dataset, we shall utilize 3D images of soil structures and results of direct flow simulations with Stokes solver [4]. We shall demonstrate how this type of models to build robust solutions on different scales including pore and macropore domains.

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# The Hidden Oxygen Sink: Carbon Dynamics in Closed Systems

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**ABSTRACT**

Precise prediction of soil organic carbon (SOC) sequestration remains a challenge due to the complex interplay between microbial metabolism and physical boundary conditions. In this study, we utilize "closed microbial ecosystems" (CES) as a controlled proxy for soil micro-environments to differentiate between transient carbon storage and long-term sequestration. We developed a mechanistic simulation model integrating the Microbial Carbon Pump (MCP) and Partial Oxidation (PO) pathways to quantify the stabilization of carbon across temporal scales.

Our findings indicate that sequestration is driven by the microbial transformation of labile precursors into recalcitrant organic matter [1]. Even in simplified microbial communities, these systems self-organize to persistently cycle carbon, providing a unique lens into the fundamental limits of carbon persistence [2]. Experimental verification using FT-ICR-MS analysis demonstrated that lignin/CRAM-like compounds increased from 34.4% to 61.0% over 38 days, confirming the formation of persistent carbon sinks. Furthermore, our model identifies a "hidden oxygen sink": as microorganisms partially oxidize organic matter to increase its Nominal Oxidation State (NOSC), the resulting compounds become thermodynamically unfavorable for further respiration [3]. By coupling gas pressure dynamics with chemical transformations, this research provides a framework for the precise assessment of carbon sequestration efficiency [4]. These results offer a scalable methodology to improve the accuracy of SOC storage predictions from the micro-aggregate to the global scale.

**Acknowledgments**

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# A spatially explicit model for watershed nitrogen fate through multi-scale integration of soil biogeochemistry and hydrology

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**ABSTRACT**

Quantifying watershed nitrogen (N) fate is critical for non-point pollution control but remains challenging due to the spatial and temporal decoupling of grid-scale biogeochemistry from watershed-scale hydrology. This limits accurate prediction of N sources, transport pathways, and time lags. To bridge this gap, we developed a novel spatially explicit model (INSIGHT), which tightly couples a high-resolution soil biogeochemical model with a distributed hydrological routing scheme. Through multi-scale data-model fusion, the model was robustly constrained using both in-situ observations across key land uses and watershed outlet monitoring data while explicitly accounting for the spatial heterogeneity of land uses and soil hydraulic properties. INSIGHT demonstrated high performance in a 42 km² agricultural-forested watershed in the lower Yangtze River, simulating streamflow and N export with accuracy (R2, 0.505–0.965, $p < 0.01$). The model accurately captured the spatial heterogeneity of water and nitrogen (N) dynamics across land uses, with strong performance for soil moisture ($R^2$=0.991) and soil N ($R^2$=0.948) in tea plantations, mixed forests, and paddy fields. Model simulations showed that annual N input totaled 660 Mg N $yr^{-1}$, dominated by synthetic fertilizer (51%), organic manure (34%), and atmospheric deposition (15%). N removal occurred mainly through crop harvest (36%), outlet export (12%), ammonia volatilization (14%), and denitrification (11%). Approximately 26.5% of input N was retained in the watershed, primarily as organic N (25.7%), while residual mineral N was low (0.8%) and influenced by precipitation variability. Agricultural soils (30.6% of area) contributed 34.7% of N export due to high fertilization rates. Subsurface flow accounted for 62.4% of N export despite representing only 43.8% of streamflow, highlighting the key role of groundwater biogeochemical retention. Sensitivity analysis showed delayed N export responses (5–30 years) to fertilizer reductions, reflecting significant legacy effects. INSIGHT provides a spatially explicit, process-based framework for high-resolution assessment of watershed N fate, supporting targeted non-point pollution management.

**Keywords:** watershed; N fate; biogeochemistry; hydrology; INSIGHT

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# Fusion simulations based on process-based modeling and AI-technology for groundwater storage and quality in the Mollisol Regions

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**ABSTRACT**

Groundwater is crucial for ensuring stable food production and environmental sustainability in the Mollisol region. However, high-intensity agricultural production activities have subjected groundwater resources in Mollisol regions to dual pressures of "water quantity imbalance" and "water quality deterioration". Accurately simulating groundwater storage (GWS) dynamics and predicting associated water quality parameters, such as nitrate ($NO_3^-$) concentrations, are central yet challenging tasks in the Mollisol regions. These challenges arise from the inherent complexity and heterogeneity of subsurface hydrological processes, coupled with often limited observational data. While process-based models such as the Soil and Water Assessment Tool (SWAT) effectively simulate hydrological and nutrient cycles, they frequently exhibit uncertainties in simulating regional GWS dynamics and pollutant transport. This study proposed a fusion simulation framework, integrating the physical mechanisms of the SWAT model with AI-technologies, aiming to sequentially correct systematic errors in simulated GWS and subsequently predict groundwater $NO_3^-$ concentrations in Mollisol regions. The framework implements a two-stage AI-enhanced modeling approach. First, a GWS error correction model was constructed. The GWS error between simulations from SWAT and derived from Gravity Recovery and Climate Experiment (GRACE) data assimilation serves as the learning objective, with multiple variables from the SWAT model used as features. These features were fed into various machine learning (ML) algorithms for training and testing to identify the best error correction model. The results demonstrated that the error correction model improves GWS simulation performance, with the coefficient of determination ($R^2$) increasing by 19.1% to 86.6% over the study period, effectively reducing systematic bias in the process-based model. Subsequently, based on the corrected GWS data, integrated with simulated driving variables from the SWAT model, a groundwater $NO_3^-$ concentration prediction model was constructed, enabling quantitative assessment of groundwater quality at the regional scale. Results indicated that the model possesses strong groundwater $NO_3^-$ concentration prediction potential in Mollisol regions. Feature importance analysis further revealed that nitrogen leaching and fertilizer application rate are the dominant factors controlling $NO_3^-$ concentration. This study demonstrated that integrating based on process-based modeling and AI-technology provides a powerful paradigm for addressing groundwater science challenges in Mollisol regions. The proposed framework not only corrected systematic biases in mechanistic models when simulating GWS but also establishes a data-driven pathway for predicting water quality, thereby providing a References method for addressing groundwater sustainability and pollution risk assessment under changing environments.

# Assessing Future Climate Change Impacts on Soil Erosion, Agricultural Nonpoint Source Pollution, and Crop Growth in the Huai River Basin

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**ABSTRACT**

Against the backdrop of global climate change, the Huai River Basin—a vital grain production base and ecological transition zone in China—faces severe challenges to its water and soil resource security and agricultural sustainability. This study employs the distributed hydrological model SWAT (Soil and Water Assessment Tool) to systematically evaluate the impacts of climate change on soil erosion, agricultural nonpoint source pollution, and crop growth in the Huai River Basin under future climate scenarios.

This study first constructed and calibrated the SWAT model tailored for the Huai River Basin, simulating the hydrology and water quality of streamflow, sediment transport, nitrogen and phosphorus migration, and crop growth. Model calibration and validation were performed using the SWAT-CUP (SWAT Calibration and Uncertainty Program) tool. Results indicated that during 2003–2021, calibration for rice, wheat, and maize yields in the study area achieved good performance, with Percent BIAS (PBIAS) values for all six sub-regions falling within ±15% during both the calibration and validation periods. Furthermore, based on streamflow observations from four hydrological stations, the model achieved overall Nash-Sutcliffe Efficiency (NSE)and $R^2$ values exceeding 0.50 during both the calibration period (2009–2013) and validation period (2014–2018), with PBIAS distributed within ±25%, indicating reliable streamflow simulations. Following streamflow calibration, sediment and nitrogen & phosphorus transports parameters were further calibrated using data from two observation sites. Results showed NSE and $R^2$ values exceeding 0.75 at both outlets, with PBIAS maintained within ±25%. This demonstrated the SWAT model's strong applicability and reliability in simulating hydrology, sediment yield, nitrogen & phosphorus transports, and crop yields in the Huai River Basin.

Building upon this fully calibrated SWAT model, this study systematically assessed the impacts of future climate change on hydrology and water quality in the Huai River Basin. Findings indicated that soil erosion within the basin is projected to significantly intensify, with potential increases in erosion intensity. Agricultural nonpoint source pollutants (nitrogen and phosphorus losses) are projected to increase in transport loads via runoff and sediment, posing potential threats to basin water quality. Crops response to future climate change are complex. While some crops may benefit from extended growing seasons, overall production stability is expected to be adversely affected by frequent extreme climate events such as high temperatures and droughts.

**Keywords:** Huai River Basin, SWAT model, Climate change, Soil erosion, Agricultural non-point source pollution

# MapBiomas Soil: Soil Information across Four Decades of Land Use and Land Cover Change

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**ABSTRACT**

The MapBiomas initiative is a collaborative network that produces annual, spatially explicit environmental information by integrating remote sensing data and cloud-based processing. Initially focused on land use and land cover dynamics, the network has expanded to thematic domains such as fire scars, surface water, and environmental degradation and has been replicated across several countries in the Global South.

Within this ecosystem, MapBiomas Soil is a thematic initiative dedicated to the production of soil information for Brazil. It adopts an iterative development model based on digital soil mapping, in which harmonized field soil observations from the SoilData repository are integrated with environmental covariates to generate annual national collections of soil maps at 30 m resolution. Since its initial release in 2021, successive collections have incorporated new soil data and covariates, progressively expanding the dimensionality of soil information.

Currently, MapBiomas Soil provides annual maps of soil organic carbon (SOC) stocks for the period 1985–2024 (0–30 cm), maps of soil granulometry (sand, silt, and clay) at 10 cm intervals down to 1 m, soil texture maps generated for six depth intervals and three classification levels, and maps of depth to soil stoniness, defined by thresholds of 50% and 90% coarse-fragment volume.

According to Collection 3 (2025), Brazil stores approximately 37.5 Gt of SOC in the topsoil in 2024. More than half of this stock is concentrated in the Amazon, while the highest average SOC densities occur in the Atlantic Forest. SOC stocks are consistently higher in clayey and silty soils and substantially lower in sandy soils, with contrasts approaching a twofold difference in savanna and semi-arid regions. Depth-wise analyses indicate a systematic increase in clay content with depth at national scale, with clayey textures predominating between 60 and 100 cm. Joint analyses of soil texture and four decades of land-use and land-cover change show that land occupation is strongly conditioned by soil physical properties: pasture expansion predominated on medium- and coarse-textured soils, agricultural expansion concentrated on finer-textured soils, and silviculture expanded preferentially where soil physical constraints limit intensive cropping.

Embedded within a broader environmental data ecosystem, these products support pixel-scale, long-term analyses of soil–land-use interactions, allowing soil properties to be examined both as conditioning factors shaping land-use trajectories and as responses to environmental and anthropogenic changes across the Brazilian territory.

**Keywords:** digital soil mapping, carbon stocks, Brazil, soil texture, machine learning.

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# Towards predicting plant uptake of trace elements with a mechanistic mass-balance model

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**ABSTRACT**

Trace elements (TEs) occur in the environment in small quantities, but can have a disproportionately large effect on humans and ecosystems. Some TEs, including lead and cadmium, are toxic to life and can have deleterious effects on human and ecosystem health, while others including copper and zinc are essential micronutrients for animals and plants. Over the past 50 years, concentrations of essential TEs in staple crops such as wheat have been declining, due in part to selection processes preferring higher yielding varieties, which also take up less nutrients from the soil. This unintended consequence is resulting in food losing its nutritional quality. The mechanisms by which this happens are still under investigation, however the impact of this on human nutrition and health outcomes is well understood. Instances of 'hidden hunger', or TE deficiencies from an energy-dense but nutrient-poor diet, are prevalent in more than one quarter of the world's population. The behaviour and effects of TEs depend largely on their concentration in the environment and their chemical form, or speciation, which is influenced by a range of soil parameters. For example, the presence of TEs including copper, zinc, selenium and iodine in food chains depends heavily on their mechanisms of adsorption, resulting in fractions either more or less bioavailable, in soils. We have developed a mass-balance model that uses easily parametrised input variables to produce accurate estimates of TE accumulation rates in soils. We have validated the model's soil accumulation function using long-term field trial data from New Zealand. However, now we seek to determine whether this model can accurately predict trace element uptake into plants, including food crops. Using data from Rothamsted Research's long-terms field trials, we have parametrized the model with a view to improving its plant uptake prediction capacity. Subsequent improvements to the model have included functions to vary soil adsorption coefficients for TEs over time, and to incorporate yearly-specific weather parameters. This research contributes to improved understanding of plant uptake of TEs, that facilitates improved management of soils leading to better outcomes for human nutrition and soil health.

**Keywords:** trace element bioavailability, biogeochemistry, soil adsorption coefficient, human nutrition, micronutrients, soil health

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# The influence of the soil cover on the reliability of soil erosion modelling on the Central Russian Upland

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**ABSTRACT**

Soil erosion is widely recognized as a major threat to soil cover and food security. The Central Russian Upland (CRU), with area 170,000 km2, is one of the most erosion-hazardous regions in Russia, what is due to the dissected relief, combined with the extensive cultivation of the highly fertile Black soils. In the northern part of CRU, the soil cover is contrasting with a predominance of Phaeozems. In the central and southern parts, the soil cover is relatively uniform with a predominance of Chernozems.

Field studies were conducted in different parts of CRU on 5 arable catchments with areas 0.1-1 km2 and 5 sites with areas 103-855 km2. Soil properties analysis at 1700 survey points were used to calculate the K-factor. Soil erodibility decrease from North to South of CRU by an average of 1.75 times. SD of K-factor in the northern part of CRU is >0.08, while in the central and southern parts is double lower.

In the post-Soviet period, part of the arable land was abandoned, especially in the 1990s and 2000s. This abandonment was driven by soil fertility. First of all, less productive Phaeozems were abandoned. Differences in the area of arable land and the volume of soil losses, calculated using different land use maps, are more than 10-fold in the northwestern districts.

Detailed estimates of soil erosion rates obtained using radiocesium and magnetic tracer methods within arable land in small catchments are in good agreement with model calculations by WATEM/SEDEM for rainfall erosion and Russian regional model of the State Hydrological Institute for snowmelt erosion. Erosion losses measured by soil morphology at a total of 2500 points are in good agreement with those modelled for the agricultural period in the Chernozem zone. However, in the northern part with a predominance of Phaeozems, significant discrepancies are observed between the modeled and measured soil erosion losses, probably due to specific soil-forming processes.

Thus, the quality of soil erosion modeling in the northern and southern parts of the CRU differs largely due to differences in soil cover. The upscaling of soil erosion modeling in the northern part is significantly more complex and requires more detailed input parameters (K-factor and land-use boundaries), compared to the southern part of the CRU. The erosion model's shortcomings include: i) insufficient accuracy in estimating the sediment deposition, both within and outside the arable land; ii) the lack of an ephemeral gully erosion calculation module.

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# Spectra-based predictive mapping of soil erosion rates in sloping croplands

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**ABSTRACT**

Erosion-induced lateral soil redistribution leads to spatially heterogenous soil composition, which can be captured through the distinctive spectral reflectance of soils under varying levels of erosion influence. This points to the potential of using remotely sensed soil spectra to map soil erosion intensity, as demonstrated by previous studies (Qi et al., 2023; Qi et al., 2024). However, it remains challenging to develop verifiable regression models that are capable of estimating soil erosion rates at high spatial resolution. A key reason for this is the lack of observational datasets for model training. In the presentation, we will report our work on spectra-based soil erosion mapping via remote and proximal sensing of cropland soils in the Phaeozem and Chernozem region of Northeast China. First, a large-scale field survey was conducted to establish a sample set (n=850), 200 of which were measured for $^{137}$Cs inventory for estimating soil erosion rates. Then, laboratory-based soil spectral modelling was adopted as a data augmentation technique to predict erosion rates for the un-measured samples. Based on the large-scale erosion dataset, point-based observations were linked with multitemporal Sentinel-2 bare soil composites to construct a spectra-based remote sensing framework for quantitative soil erosion prediction and mapping. Using the predicted soil erosion map, we will further present the spatially varying relationship between soil erosion and crop productivity, as also confounded by biophysical conditions and the interannual variation in precipitation.

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Qi, L., Shi, P.*, Dvorakova, K., Van Oost, K., Sun, Q., Yu, H., van Wesemael, B. Detection of soil erosion hotspots in the croplands of a typical black soil region in northeast China: Insights from Sentinel-2 **multispectral** remote sensing. Remote Sensing, 2023, 15(5), 1402.

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# InSAR-based Quantitative Remote Sensing of Spatiotemporal Characteristics of Soil Erosion

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**ABSTRACT**

Soil erosion degrades ecosystem services, decreases agricultural productivity, reduces economic returns, and deteriorates water resources, significantly threatening the World's agricultural soils. Various techniques are available to measure or estimate soil erosion across different scales. Monitoring soil erosion is one of the fundamental approaches required by sustainable land management. However, there is a lack of quantitative measuring techniques that can track changes in soil erosion processes at high spatiotemporal resolution. Land surface deformation has been successfully monitored at different scales with Interferometric synthetic aperture radar (InSAR). As soil erosion is an analogous surface deformation, we aim to develop an InSAR-based method to monitor detachment, translocation and deposition at high spatiotemporal resolution (e.g., mm soil loss, short revisit times) and attribution models are developed for driving factors and for prediction. Three case studies on the use of this new methods in landslide and soil erosion monitoring on the Tibet Plateau, Loess Plateau and Northeast China are presented and discussed.

Keywords: quantitative remote sensing, soil erosion processes, sediment transport and deposition, land deformation, machine learning

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# Assessments of Gully Erosion Susceptibility in Typical Thick-Layer Mollisol Region of Northeast China

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**ABSTRACT**

Gully erosion is a predominant form of land degradation in arable lands, leading to soil degradation and threatening ecological security and food production. However, current studies on gully erosion susceptibility (GES) often suffer from variable redundancy and limited model interpretability, which compromise model accuracy and generalizability. To overcome these challenges, this study takes Keshan County, with an area of 3,186.11 km2, located in the typical thick-layer Mollisol region of Northeast China, as a case study. The ten key driving factors affecting gully erosion were selected, and four machine learning models—random forest (RF), logistic regression (LR), support vector machine (SVM), and extreme gradient boosting (XGBoost)—were employed to assess the GES in the study area. Results showed that models based on the ten-factor achieved comparable performance to those using the full-factor across accuracy, $R^2$, area under the curve (AUC), and error indices. Among them, the XGBoost demonstrated the highest predictive accuracy, with the AUC values of 0.904 and 0.881 in training and testing stages, respectively, indicating robust generalization and stability. Notably, the spatial distribution analysis revealed that different models consistently delineate the GES areas. Areas of very low susceptibility constitute the majority of the study area while regions with high susceptibility are mainly concentrated in areas with complex topography. SHapley Additive exPlanations (SHAP) based interpretability analysis further highlights the topographic position index (TPI), annual average temperature (Temp), and digital elevation model (DEM) as the most influential factors, exhibiting pronounced nonlinear impacts on the GES. Overall, the findings offer an effective and interpretable approach for assessing the GES, which can directly support gully erosion prevention and contribute to the long-term protection of Mollisol resources.

**Keywords:** Gully erosion susceptibility; Multi-model factor selection; Machine Learning; SHAP method; Chinese Mollisol Region

# Pasture Restoration Improves Runoff, Soil loss, and Sediment Sorting in a Brazilian Karst Basin

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**ABSTRACT**

Karst landscapes are fragile environments and are difficult to restore once disturbed, causing soil loss and downstream sedimentation. Because of the expansion of the agricultural frontier in the Brazilian savanna during the last 60 years, its karst areas have been subjected to severe degradation, affecting the sustainability of farmers in the region. The research aimed to quantify the erosion rates occurring in degraded pastures in the Brazilian savannah and to evaluate the effectiveness of its restoration, the possible correlation of soil loss with runoff, and whether Gerlach collectors, a simple and unexpensive method to assess soil loss in developing countries, could be used in the erosion assessment in karst areas. In this study, runoff and soil loss in degraded and restored pastures, and in natural savannah were assessed during two years using Gerlach plots at three sites (farms) of the Vermelho river basin, in Brazil. The farms were treated as randomized blocks, and the treatments were degraded pasture, restored pasture, and natural savanna vegetation. After 2 years of pasture restoration, runoff was reduced by 40% and erosion decreased by 50%-80% in the restored pasture treatments, compared to the degraded pasture condition. In most plots, the sediment was enriched with fines, reducing the silting potential of sinkholes and underground rivers in the Vermelho river basin. Furthermore, Gerlach collectors, which are simpler and cheaper than traditional erosion plots, emulated the latter in terms of quantitative soil erosion assessment, facilitating soil loss monitoring in tropical karst areas.

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# Influences of slope gradient and length on runoff and soil erosion of arable farmland in Northeast China: A modeling approach with APSIM

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**ABSTRACT**

The black soil region has many ridge cultivation slope farmland, which results in a serious threat of soil water erosion and further corn yield decreasing. Agricultural Production Systems Simulator (APSIM) has been shown to accurately simulate the growth of crop under conservation tillage, whereas few studies have investigated the soil erosion and runoff throughout the complete growth period of crop. In this study, APSIM was calibrated and validated by soil characteristics and corn yield data under rotary tillage (RT), no-tillage without straw mulching (NT), no-tillage with straw mulching (NT-SM) and strip tillage with straw mulching in wide rows (ST-SM) treatments, which were used to investigate the regularity of soil erosion and runoff under slope gradient 3°, 6°, 9°, 12°, 15°, 18°, 21°, 24° as well as length 50 m, 100 m, 250 m, 500 m, 750 m, 1000 m, 1250 m under long-term (1981-2023) meteorological data. The result showed APSIM effectively simulated soil erosion amounts, runoff depth and corn yield with normalized root mean square errors (NRMSE) of 48.30-93.25%, 37.41-77.55% and 5.98%, respectively. The simulated soil erosion amounts significantly increased with slope gradient and length, whereas simulated runoff depth increased with no significant difference. Tillage and climate significantly affected simulated soil erosion amounts (standardized path coefficients 0.56 and 0.63, -0.88 and -0.92) and runoff depth (0.14 and 0.15, 0.50 and 0.56). Conservation tillage (NT-SM and ST-SM) significantly decreased soil erosion amounts and runoff depth compare with rotary tillage, reduction rate progressively increased with slope length and gradient by more than 96% and 25%, respectively. However, reduction rate of simulated soil erosion amounts and runoff depth of NT treatment progressively decreased with slope gradient by 16.62-15.30% and 14.23-12.89%, and significantly lower than NT-SM and ST-SM treatment. Corn yield was decreased under NT and NT-SM treatments by 3.16% and 7.02% compare with RT treatment. The highest corn yield was found at ST-SM treatment 11.40 t ha-1 (2.89%). In conclusion, APSIM was accurately applied to simulate soil erosion and runoff in slope farmland, the effect of decreasing soil erosion and runoff of no-straw-mulching practice was underperforms compared with straw mulching practice in slope farmland. NT-SM treatment was most effective in resisting soil erosion under slopes below 6° and 250 m, ST-SM treatment was more suitable for slopes above 9°and 500 m and increased corn yield.

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# Impacts of Soil Erosion on Soil Organic Carbon Dynamics and Carbon Neutrality

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**ABSTRACT**

Agricultural soils are key carbon reservoirs for achieving carbon neutrality and climate mitigation. Soil organic carbon (SOC) is stabilized within aggregates that limit microbial decomposition and erosion losses. However, soil erosion can disrupt aggregates, enhance SOC mineralization and $CO_2$ emissions, and transport SOC to aquatic systems, reducing carbon stocks in agricultural fields. Although some eroded SOC may be deposited and stored in floodplains or sediments, potentially offsetting emissions, the net effect of soil erosion on carbon neutrality remains uncertain. This study evaluates the impacts of soil erosion on carbon neutrality by jointly considering SOC loss, transport, and redistribution, together with greenhouse gas (GHG) emissions ($CO_2$, $CH_4$, and $N_2O$) from aquatic and depositional environments, changes in fertilizer use, and biomass productivity. Soil erosion effects were examined using four scenarios: (1) SOC transport only; (2) SOC transport with $CH_4$ emissions from wetlands; (3) SOC transport with $CH_4$ and fertilizer-induced $N_2O$ emissions; and (4) SOC transport with $CH_4$, $N_2O$, and biomass changes. Previous studies estimate global SOC loss from soil erosion at approximately 0.9–1.31 Pg C $yr^{-1}$, with further increases projected under climate change scenarios (RCP 2.6 and RCP 8.5). In steep alpine agricultural regions of South Korea, annual SOC losses range from 11.8% to 16.5%, with particulate organic matter being more vulnerable to erosion than mineral-associated organic matter. Erosion-driven SOC redistribution increases $CO_2$ and $CH_4$ emissions in depositional zones and is associated with elevated $N_2O$ emissions from increased fertilizer inputs and reduced biomass productivity, collectively exerting negative impacts on carbon neutrality. Current IPCC greenhouse gas accounting frameworks do not adequately account for erosion-induced SOC loss and redistribution, leading to uncertainties in agricultural carbon budgets and emission assessments. This study demonstrates that reducing soil erosion contributes not only to mitigating sediment and turbidity but also to enhancing carbon neutrality through SOC conservation and reduced GHG emissions. Further research is needed to develop integrated quantitative approaches linking soil erosion, SOC dynamics, and greenhouse gas emissions and to incorporate these processes into future policy and management strategies.

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# Impacts of cascading check dams on sediment yield in the middle Yellow River Basin: Insights from 50 years of grid-cell-level simulation

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**ABSTRACT**

Check dams, globally built as vital engineering interventions for controlling soil erosion, form complex cascading systems in streams that pose significant challenges for assessing spatiotemporal dynamics of sediment yield (SY) at large basin scale. This study proposed an integrative model framework combining dynamic sediment trapping efficiency of cascading check dams with the Revised Universal Soil Loss Equation (RUSLE), index of connectivity (IC), and sediment delivery ratio (SDR). This model was applied to evaluate grid-cell-based distribution of SY and sediment trapped by check dams during 1970-2019 in the middle Yellow River Basin (with over 47000 check dams). The efficiency coefficient of proposed model increased to 0.71 compared to model ignoring sediment trapping of check dams (0.59). Totally $3.84 \times 10^9$ t of sediment was trapped by check dams over the 50 years, representing 14.41% of actual SY and constituting 41.49% of designed storage capacity. The sediment reduction contribution by check dams ($SRC_{dam}$) decreased from 25.27% in the 1970s to less than 10% in recent years. Notably, the impacts of check dams on SY exhibited considerable spatial heterogeneity, with $SRC_{dam}$ ranged from 73.9% to 0.9% and the proportion of accumulated sediment to storage capacity of check dams ($SAR_{dam}$) varied from 78.1% to 1.1% among sub-basins. The $SRC_{dam}$ increased linearly with check dam density and the share of area they controlled, whereas $SAR_{dam}$ increased with SY from upstream of the check dams as a logarithm function ($P < 0.001$). Further, there was evident trade-off between $SRC_{dam}$ and $SAR_{dam}$ in some sub-basins, indicating that the number of check dams in these basins is insufficient or overmuch. This study provides a practical and data-efficient method for assessing sediment trapping and reduction by cascading check dam systems in large basins, offering valuable insights for optimizing check dam arrangement to enhance their sediment control effectiveness in erosion-prone regions.

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# Mobilizing Legacy Data for Continental-Scale Erosion Modelling: The MapBiomas SoilData Initiative in Brazil

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**ABSTRACT**

Soil erosion remains one of the most critical global environmental challenges, demanding advanced modelling strategies to characterize its spatial and temporal dynamics. In 2025, the MapBiomas network—an open, collaborative, and multi-institutional initiative—launched a nationwide effort in Brazil to systematically map erosive features, with a specific focus on ephemeral and permanent gullies. This study presents the strategy and implementation of the SoilData Repository erosion community, a centralized infrastructure developed to organize, standardize, and publish erosion records for broad scientific reuse.

To address the persistent issue of data fragmentation, the initiative aggregates erosion records from any year and across the entire Brazilian territory. The database supports flexible data inputs, ranging from single geoReferencesd points indicating gully occurrence to detailed spatial delineations of eroded areas. By harmonizing heterogeneous datasets within a standardized, open-access, and collaborative online platform, the initiative advances open-data practices in soil erosion research.

The resulting database provides the essential ground-truth foundation for integrating field observations with satellite imagery and machine learning techniques to map the spatial extent of erosive features. This workflow enables the upscaling of localized field assessments to national and continental monitoring systems, effectively bridging the gap between site-level observations and large-scale erosion modelling. To ensure traceability, reproducibility, and proper attribution, all datasets published in the SoilData Repository are assigned Digital Object Identifiers (DOIs). This initiative demonstrates a replicable open-science framework and contributes to global efforts toward harmonized and scalable soil erosion monitoring and modelling.

**Keywords:** SoilData Repository, Gullies, Open Science, Machine Learning, Land Degradation.

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# An Evaluation of the Quantity–Intensity Relationship of Potassium (K) on Some Lowland Rice-Growing Soils

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**ABSTRACT**

The potassium (K) supplying capacities of some lowland rice-growing soils were investigated by employing the quantity-intensity (Q/I) approach. Surface horizons of three soils were characterized by measurement of physico-chemical analysis, quantity-intensity adsorption isotherm for K, and X-ray diffraction of clay fraction. The values of potential buffering capacity (PBCK), labile K (KL), non-specific sites K (KO), specific sites K (KX), equilibrium activity ratio (AReK) and free energy change (−ΔG) were esti-mated from the quantity-intensity curve. The values of PBCK varied from 109.10±10.56 to 117.20±8.36 CmolcKg−1, AReK ranged from 0.0050±0.012 to 0.340±0.004 (molL−1)1/2, and KL differed in the amounts of 0.436±1.47 to 4.793±1.41 CmolcKg−1. The KX values ranged from 0.016±0.98 to 1.044±1.07 CmolcKg−1, −ΔG values differed from −13.30±4.21 to −8.52±3.19 KJmol−1. K present in specific and non-specific sites of clay was changed with clay mineralogy. Higher cation exchange capacity and organic carbon favored the labile K pool. The high AReK ratio indicated higher availability of labile K, and the bulk of that K was preferentially held at the planar surface of the clay crystals. High PBCK values indicated that K availability in these soils was excellent. PBCK was positively correlated with organic carbon (OC) and cation exchange capacity (CEC). The changes of AReK, PBCK, KL, and ΔG were related to the contents of pH, CEC, OC, clay %, and clay mineralogy of the soil. K fertilization is not required in a paddy soil with higher organic carbon and the presence of illite clay minerals.

**Keywords:** Quantity-intensity relationship, labile K, specific K, free energy change, equilibrium activity ratio, and potential buffering capacity of soil.

# Reconciling carbon sequestration value and soil health benefit of organic amendments

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**ABSTRACT**

Large volumes of organic amendments including crop residues, compost, manure, biosolids and biochar are increasingly being used as a nutrient and carbon (C) source to improve soil health, and to promote C sequestration (Thangarajan et al., 2013). Organic amendment input to soil is likely to impact C sequestration in soil through (i) increased crop biomass accumulation by enhancing soil physical, chemical and biological properties, and (ii) biochemical stabilisation of organic amendment-derived C in soil (Enebe et al., 2025). However, the enigma of C distribution in organic amendments, which determines whether and how these two processes couple to promote C sequestration in soil remains unknown. Furthermore, one of the problems with the use of organic amendments as a means of terrestrial C sequestration is their relatively fast rate of degradation, leading to the release of greenhouse gases (GHG) including, thereby becoming a source (rather than a sink) for GHG emission. This presentation provides a quantitative analysis of the novel approaches to reconciling soil health benefits with the C sequestration value of organic amendments in farming systems. This presentation will cover the critical analysis of the literature data on the influence of various organic amendments (e.g., compost, manure, biosolid, biochar) application on soil physical, chemical, and biological fertility, and C sequestration, and presents the results of a ***meta-analysis*** of these data from publications. A *treatment effect size estimator* commonly employed in meta-analysis is the magnitude of an experimental treatment mean (i.e., with organic amendment application), relative to the control treatment mean (i.e., without organic amendment application). A typical effect size metric is the response ratio or the relative impact on a measured parameter (e.g., soil bulk density) following organic amendment application compared to that in control treatment. The results from the meta-analysis work have indicated that organic amendment application modulates physical (e.g., moisture retention), chemical (e.g., nutrient accumulation), and biological (e.g., microbial activity) properties of soils while contributing to C sequestration.

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# Synergistic Microbial Consortia from the Black Soldier Fly Mediate Broad-Spectrum Suppression of Plant pathogens

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**ABSTRACT**

Plant diseases cause 20%-40% of global annual crop losses. Meanwhile, chemical fungicides exacerbate environmental degradation through soil and water contamination, demanding microbial biocontrol. Exogenous microbes from sources like aquatic environments and composts exhibit broader advantages in diversity, functional specificity, environmental adaptability, and large-scale application potential. Insects are another underexplored beneficial microbe reservoirs though their harnessing faces challenges. Conventional single-phase screening methods isolate either volatile or liquid metabolites and fail to capture the multi-dimensional synergies in plant growth environments. We develop a dual-phase screening strategy that integrates volatile organic compounds (VOCs) and liquid-phase secondary metabolites (LMs). Using black soldier fly (BSF) larval frass as a microbial reservoir, we targeted strains with coordinated production of both liquid phase and gas phase anti-pathogen metabolite, optimizing inter-strain interactions to construct an 8-member synthetic community (SynCom). The SynCom inhibited potato black scurf by 70%, significantly higher than individual strains (15%-60%). This advances the application of BSF-derived microbial community in sustainable agriculture, provides ideas for bio-control of plant diseases.

**Keywords:** Synthetic community, plant pathogens, black soldier fly

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# Current Situations of Antibiotic Resistance Genes in Compost, Soil, and Sediment in Vietnam

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## ABSTRACT

In Vietnam, antimicrobial resistance (AMR) has become an emerging environmental and public health concern due to the widespread use of antibiotics across various sectors, particularly in livestock and aquaculture production systems. Consumption of antibiotics can provide selective pressure, leading to the development of AMR. Antibiotic resistant bacteria (ARB) are often weakly pathogenic commensal bacteria that generally remain asymptomatic in healthy hosts. Antibiotic resistance genes (ARGs) can easily spread AMR among microorganisms via horizontal gene transfer, and when acquired by pathogenic bacteria, they could pose a greater threat to human health. In the soil environment, livestock can excrete ARGs through their manure, and the subsequent use of manure compost can alter the soil's physicochemical properties, thereby affecting the abundance of ARGs. In the aquatic environment, aquaculture waste can introduce ARGs into the water, which may eventually accumulate in sediment. Understanding the distribution of ARGs is crucial for assessing environmental risks and developing effective mitigation strategies. The objective of this study is to clarify current situations of ARGs in compost, soil, and sediments in Vietnam, and to provide a better understanding of how compost application and different aquaculture practices influence the abundance of ARGs in the environment.

Compost, soil, and sediment samples were collected from agricultural farms and shrimp ponds in central (Hue City) and southern Vietnam (Ho Chi Minh City and Tay Ninh Province) in September 2024, and in March and September 2025. In total, 128 soil samples were collected from 17 farms at different depths (up to 100 cm, depending on the site) in fertilized and unfertilized plots, including repeated sampling of the same sites at different times. Twenty-nine compost samples collected were made from cow, chicken, and quail manure, with or without additives (e.g., rice husk, rice straw, biochar, etc.). Seven sediment samples were collected from shrimp ponds (intensive and extensive). Six ARGs (*sul1*, *sul2*, *sul3*, *tetM*, *tetW*, and *ermB*) were selected as target ARGs. Additionally, 16S rRNA gene and the integron integrase gene *intl1* were quantified using qPCR.

Our results indicate that *sul1* and *sul2* were commonly detected in most sampling sites. In both compost and soil, the highest levels of target ARGs were found in Dan Dien commune, Hue City. For compost, ARGs abundance in chicken manure compost was higher than in cow manure compost. For soil, ARGs levels were greater in fertilized soil compared to unfertilized soil. Generally, ARGs abundance decreases with increasing soil depth. For sediment, ARGs levels were higher in intensive shrimp ponds than in extensive shrimp ponds. Our findings highlight the elevated levels of ARGs in chicken and shrimp farming, underscoring the urgent need for reducing the spread of ARGs and ARB.

**Keywords:** antibiotic resistance gene, compost, sediment, soil, Vietnam

# $CO_2$ emission from forest soils in Western Japan as affected by water repellency

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**ABSTRACT**

The planetary burden on the Earth's atmosphere due to continued surge in emissions of greenhouse gases (GHGs) has become a serious global threat over the past several decades. Soil, as the largest terrestrial C sink, is susceptible to global warming and the release of GHGs. Soil water repellency is a phenomenon that causes soil to resist spontaneous wetting, influencing potentially all water-involved processes in soils. With increasing water repellency, the thickness of water layers surrounding soil particles becomes significantly thinner, restricting the spatial distribution of water in soil matrix, possibly influencing microbial activities in soil. The objective of this study was to determine the effects of water repellency on $CO_2$ emission from forest soils of Western Japan under different types of vegetation.

Water-repellent soil samples were collected from Japanese cedar (CED) Japanese cypress (CYP), and cedar and cypress mixed (MIX) forests in Tsuyama, Okayama prefecture, Japan. Soils were collected at 0–5 cm (U) and 5–10 cm (L) depths. According to the Köppen-Geiger climate classification, the climate of the area is warm temperate fully humid (Cfa). The litter layer composed of dry leaves, twigs, and the partially decomposed litter mat on the forest floor was carefully removed before collecting soil samples. The contact angle was measured using the sessile drop method. Sub-samples of air-dried soil (10 g) were placed in 100 mL glass vials and sealed immediately using a rubber septum after adding 3 mL of deionized water. The vials were incubated in a chamber at 25°C and the emission of $CO_2$ was measured using gas chromatography. Measurements were taken at 15, 30, 45, 60, 90, and 120 min incubation periods. After 2 h, the vials were opened, covered with polyethylene film (0.02 mm thickness), and kept in the incubator until further measurements. The vials were flushed with atmospheric air, sealed with a rubber septum, and kept incubator for 30 min before taking measurements at 1, 3, and 7 d incubation periods.

The top layers of soils from all three vegetation types showed higher levels of repellency than the lower layers. The emission of $CO_2$ showed two peaks, one at 15 min and the other at 24 h. In CED, CYP and MIX soils, less repellent lower layers showed higher peak emission of $CO_2$. The peak emission of $CO_2$ showed significant ($p < 0.05$) negative linear correlation with water repellency of soil. This effect of water repellency can lead to overall low rates of carbon emission from soils supporting the C sequestration and enhancing the terrestrial C stocks. Understanding the relation of soil water repellency to GHG emissions would provide comprehensive insight of GHG flux from forest soils.

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# Facultative heap compost effects on soil $N_2O$, $CO_2$, and $CH_4$ emissions under aerobic incubation

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**ABSTRACT**

Organic compost is widely applied to enhance soil quality, yet its effects on greenhouse gas (GHG) emissions remain uncertain. This study examined the impact of various facultative heap composts on the emissions of nitrous oxide ($N_2O$), carbon dioxide ($CO_2$), and methane ($CH_4$). Loamy sand soil (collected from Hue city, Vietnam) was amended at 2% (w/w) with three compost types: immature cow compost (C-1M, 1 month), mature cow compost (C-7M, 7 months), and poultry compost (P-9M, 9 months). All treatments were adjusted to 60% water-holding capacity (WHC) and incubated aerobically at 30°C for 56 days. Gas emissions were measured on days 0, 3, 7, 14, 21, 35, and 56. An application of mature compost (C-7M and P-9M) significantly increased cumulative $N_2O$ emissions from the soil. Poultry compost application led to higher $N_2O$ emissions than cattle compost, likely due to a greater nitrate content and a lower C/N ratio, which promote both nitrification and denitrification. The highest $CO_2$ emission occurred in the C-1M treatment, whereas cumulative $CO_2$ did not differ significantly among C-7M, P-9M, and the control. Notably, more $CH_4$ was emitted under aerobic conditions, and compost addition increased $CH_4$ emissions. These findings emphasize that compost characteristics (e.g., raw material, maturity, mineral N content, C/N ratio) are key determinants of soil GHG emissions. Optimizing these factors should be integrated into compost production and field application guidelines to mitigate GHG emissions.

**Keywords:** *Carbon dioxide, facultative heap composts, methane, nitrous oxide, Vietnam*

# $^{15}N$ tracing reveals nitrogen uptake dynamics and retention under contrasting irrigation and residue management in paddy soils

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**ABSTRACT**

Rice residue management is a major agro-waste issue influencing nitrogen (N) fate in paddy systems, yet their combined effects on N uptake dynamics and soil N retention remain insufficiently quantified. To address this, we conducted a mesocosm experiment using soils collected from a farmland comprising six management treatments that crossed two irrigation regimes (water-saving vs. conventional flooding) with three residue options (straw removal, straw return, and weed-mat cover).

A 5 atom% $(^{15}NH_4)_2SO_4$ tracer, consistent with the field fertilizer formulation, was applied during two topdressing fertilizations to evaluate fertilizer-derived N uptake and retention across treatments. Plant sampling was performed 21 days after each $^{15}N$ application to assess $^{15}N$ enrichment and allocation. In addition, soil and pore water samples (if present) were also collected during the second sampling to calculate the $^{15}N$ mass flow among the six treatments.

Preliminary $^{15}N$ tracer results revealed contrasting responses between irrigation regimes. In conventional flooding, the addition of carbon sources such as straw return or weed-mat cover appeared to provide extra carbon sources for anaerobic denitrification, reducing $^{15}N$ uptake efficiency by rice plants. This pattern was consistent across both topdressing applications. In contrast, the water-saving irrigation treatments exhibited lower overall $^{15}N$ recovery compared to flooded conditions, yet the addition of carbon did not induce N limitation. Notably, the straw-return treatment under water-saving irrigation showed the highest $^{15}N$ uptake efficiency among all treatments, which likely due to greater oxygen availability that enhanced straw mineralization and nutrient recycling, thereby alleviating N constraints. Ongoing quantitative PCR and 16S rRNA sequencing analyses will further clarify the development and distribution of denitrifying microbial communities among the different management practices.

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# Better agro-waste management for soil health

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**ABSTRACT**

Management of organic wastes derived from agricultural production and food consumption is key to soil health and the development of a regenerative society. In response to the world's growing population, the agricultural sector has met the high demand for more cereals, vegetables, and meat. Organic wastes from these productions often contain high contents of nutrients such as nitrogen and phosphorus, which may be unexpectedly discharged into the environment, deteriorating water quality, or emitting greenhouse gases (GHGs). Moreover, antibiotic resistance genes derived from the livestock industry pose a threat to pandemic risks by contaminating food and water.

We have studied how to wisely use the agro-waste materials mentioned above for soil health conservation: namely, (1) nutrient leaching and GHG emissions from livestock manure compost, (2) biochar application to the soil for mitigation of GHG emissions and for improving water qualities in rural areas, (3) a catch crop-biological soil disinfestation system, (4) use of sediment microbial fuel cells for water quality improvement and less GHG emissions, and (5) dissemination of antibiotic resistance genes in soil.

The presentation will report that (1) similar nitrate leaching occurred both from organic and inorganic N sources after several years, and mature compost can be used for GHG reduction, (2) advanced biochar reduced nitrous oxide emissions from soil, but the biochar's function was declined with aging if the biochar was pyrolyzed at a lower temperature of 500°C rather than 800°C, (3) the catch crop-soil disinfestation system can absorb residual nutrients from the soil after the main crop and reduce nitrous oxide emissions in biological soil disinfestation, (4) application of SMFCs to agricultural drainage sediment and paddy soil was effective in reducing phosphorus release and GHG emissions from the soils, and (5) antibiotic resistance genes were often found in topsoil amended with livestock waste compost. We need to study the efficient use of organic agro-wastes to establish environmentally positive agricultural systems based on soil health in the future.

**Acknowledgments**

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# Anaerobic fermentation of food waste to connect fork to farm and minimize greenhouse gas emissions

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## ABSTRACT

Reduction of emissions in food waste management, valorization of waste streams, and organic carbon management for sequestration and soil health are becoming increasingly relevant as we approach climatic tipping points. Lactic acid fermentation of food waste has the potential to address and connect these issues, creating improved circularity through application of a simple biotechnology. Lactic acid fermentation can initiate breakdown of a wide range of organic materials through application of a *Lactobacilli* inoculated bran or spray in anaerobic conditions, producing a stable organic soil amendment in a short period of time.

This process, sometimes known as 'Bokashi', is currently used to manage food waste and produce an organic amendment at domestic scales, but further research is needed on carbon storage possibilities and socio-economic constraints to scale up. To date, the greenhouse gas emissions during food waste fermentation or subsequent soil burial have been little studied but are key in assessing the potential environmental impacts and benefits of this method and determining how much carbon could be returned to soil.

Through lab scale incubations using a model food waste comprising of potato and cabbage, we found that emissions were very low. Per kg of feedstock, we measured emissions of 150 – 250mg $CO_2$, and less than 5µg of either $CH_4$ or $N_2O$, after 21 days of closed fermentation. For comparison, literature values for composting of organic municipal waste including food waste show 50 – 60g of $CO_2$, 800 - 900 mg of $CH_4$ and 60 – 70mg of $N_2O$ can be released per kg of input waste on average (Nordahl et al., 2023). Our results therefore indicate a significant possible reduction in emissions and increase in carbon retention.

Results from further fermentations under aerobic disturbance treatments, in which food wastes were fermented in vessels with a large airspace or frequent opening, also indicate that aerobic disturbance influences $N_2O$ emission during fermentation. This has significant implications on ideal fermentation methods at scale.

These initial findings highlight the potential benefits of integrating bokashi-style fermentation into existing food waste management systems, both in minimizing greenhouse gas emissions and in preserving carbon and nitrogen in a form suitable for soil application.

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# Silicon Rich Biochar from Crop Residues Reduces Heavy Metals in Soil and Paddy Rice in Central Vietnam

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**ABSTRACT**

Heavy metals including Cd and Pb are the main elements of paddy soil contamination. Cd and Pb have impacts on rice crop and people health. The current study assessed the effectiveness of residue-based biochar with high Si content in removing heavy metals (Cd and Pb) from soil-plant systems. A factorial design with four replicates was used to set up the pot experiment. Rice husk and peanut shell residues were pyrolysed to create Si rich biochar and applied at varying rates (0, 2.5, 5.0, 7.5, 10.0 and 15.0 g/kg soil). The contents of soil and plant Cd and Pb were recorded. The results of the investigation demonstrated that the content of Cd in rice soil was higher than the permitted limit. Utilising Si-rich biochar from crop residues could be an efficient way to lower the concentration of heavy metals in rice soil and crop. The most effective adsorption method for removing Cd and Pb from soil was rice husk biochar. The application of these biochars considerably ($p<0.05$) decreased the Cd and Pb in the soil and rice shoots, demonstrating the potential of biochar application in rice soil. While application of 15 g/kg soil of Si rich biochar from rice husk decreased Cd by 21.6% and 31.2% Pb from soil and 31.7% Cd and 35.9% Pb in rice shoots. Therefore, Si rich biochar from rice husk with a high adsorption effectiveness may be a viable substitute source for lowering the buildup of heavy metals and could be the promising and ecological alternatives to synthetic material for heavy metals removal in the soil - plant system.

**Keywords:** Heavy metals, Residues-based biochar, Rice crop, Si content.

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# PFRD-Net: An Optimized U-Net Architecture for Robust Detection of Agricultural Plastic Film Residue in UAV Imagery

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**ABSTRACT**

Plastic film residue (PFR), arising from the long-term use of agricultural plastic mulching, has emerged as a pervasive non-point source pollutant, severely threatening soil health, crop productivity, and environmental sustainability. Despite growing recognition of this "white pollution," a critical gap remains in the ability to rapidly, accurately, and quantitatively assess its spatial distribution. This technological shortfall leads to inefficient, non-targeted mitigation measures. Addressing this urgent need, this study develops and validates a comprehensive, multi-stage analytical framework based on unmanned aerial vehicle (UAV) imagery for high-resolution PFR detection and quantification. A dedicated UAV-based PFR image dataset was first constructed. Three state-of-the-art semantic segmentation models (DeepLabV3+, SegFormer, and U-Net) were systematically trained and evaluated. Performance was rigorously assessed using key metrics: mean Intersection over Union (mIoU), mean Pixel Accuracy (mPA), mean Precision (mPrecision), and mean Recall (mRecall). Comparative analysis identified the U-Net architecture as the superior model for initial surface PFR detection, achieving a benchmark mIoU of 88.01%. To further enhance segmentation precision, an advanced model was developed by strategically fusing U-Net with EfficientNet. This hybrid approach yielded significant improvements, increasing mIoU by 3.07%, mPA by 2.72%, and mPrecision by 1.04%, thereby establishing a more robust solution for pixel-level mapping of surface-residing PFR. Recognizing that surface detection alone is insufficient for total pollution assessment, the framework innovatively extends to estimate the often-concealed PFR within the plow layer. A sophisticated multi-model fusion strategy was engineered for this purpose, integrating four distinct machine learning algorithms (Multiple Linear Regression, Random Forest, Support Vector Regression and XGBoost). To maximize predictive accuracy and generalizability, a rigorous optimization protocol was implemented, combining random search for hyperparameter tuning with five-fold cross-validation. This design ensures the model's adaptability across diverse regional agricultural settings. The integrated framework presented herein delivers a novel, scientifically grounded, and operationally practical tool. It empowers rapid, large-scale PFR assessment, providing the critical data evidence-based environmental governance, guide targeted remediation actions, and underpin policies for sustainable agricultural management. This work bridges a crucial technological gap, offering a direct pathway from remote sensing data to actionable insights for combating agricultural plastic pollution.

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# Evaluating nutrient dynamics in marginal soils amended with biochar and torrefied biomass with Plant Root Simulator probe

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## ABSTRACT

Biochar-based amendments are widely regarded as a promising strategy for improving nutrient availability in degraded soils. However, the extent to which feedstock type, processing conditions, and soil characteristics influence their nutrient-enhancing properties is unclear. This study evaluated the nutrient supply characteristics of biomass amendments produced via torrefaction (220–300 °C) and pyrolysis (450-550 °C), applied to marginal soils of contrasting textures. A factorial laboratory incubation experiment was conducted with four factors at two levels each: soil type (clayey, sandy), feedstock (Loblolly pine, Mesquite), thermal treatment (torrefied, pyrolyzed), and application rate (5%, 20% dry weight), along with two unamended controls for each soil type. Treatments were replicated three times in a completely randomized block design. Nutrient supply rates were monitored in-situ over 16 weeks using Plant Root Simulator (PRS™) probes, with soil burial and retrieval at 2, 4, 8 and 16 weeks. The sandy soil exhibited very low organic carbon (OC, 0.10%), nitrogen (N, 0.01%), and cation exchange capacity (CEC, 5.6 cmol+/kg), while the clayey soil had higher CEC (35.2 cmol+/kg), moderate OC (1.4%), and low N (0.12%). Pyrolyzed biomass had alkaline pH (9.0-10.7), higher fixed carbon (FC, 70–75%) and lower volatile matter (VM, 13–20%) than torrefied forms (pH: 4.3-6.4, FC: 19-26%, VM: 71-80%). Pyrolyzed Mesquite contained greater macronutrient concentration (N: 2%, P: 2.8 g/kg, K: 18 g/kg), up to six to eleven times, higher than Loblolly pine. Torrefied biomass exhibited lower overall nutrient levels, though Mesquite consistently outperformed pine. Following amendment and incubation, soil nitrate declined across treatments, particularly with high-rate torrefied amendments, likely due to sorption and N immobilization. Soil K availability increased with application rate, with pyrolyzed Mesquite being most effective. Soil P response was variable; torrefied Mesquite increased available P in clayey soil at higher application rates, whereas pyrolyzed pine enhanced P availability in sandy soil with increasing rates but reduced it in clay. These results highlight the need to understand nutrient profiles and bioavailability in thermally treated biomass and to tailor amendment strategies to specific soil types.

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# Effects of Application of Ferment Solution Produced from Discarded Vegetable Leaves on Soil Microbial Community and Celery Growth

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**ABSTRACT**

A huge amount of waste vegetable leaves is generated during greenhouse production of vegetables. Discarded leaves of Chinese cabbage were collected and anaerobically fermented to manufacture a ferment solution rich in nutrients, probiotics and enzymes. To study the effects of application of the ferment on soil nutrients and microbial communities, a field experiment on celery cultivation was conducted in suburban Shanghai. It included four treatments: spraying 2% of the ferment solution (FH), spraying 1% of ferment solution (FL), application of chemical fertilizer (CF), and control (CK). The results indicated that the content of available N and P in the soil by the FH treatment was significantly higher than by the other treatments and CK. Moreover, the activities of acid phosphatase, alkaline phosphatase, and urease in the soil by the FH treatment were significantly higher than those by CK ($p< 0.05$), and the activity of dehydrogenase by the FH was significantly higher than by the CF ($p< 0.05$). The FH treatment stimulated the growth of celery plants significantly. The celery yield by the FH treatment was 23% and 43% higher than by the CF and CK ($p< 0.05$); while the incidence of sclerotinia rot in the celery by the FH was 44% and 58% lower than by the CF and CK ($p< 0.05$), respectively. Both the FH and FL treatments improved soil microbial diversity. A total of 158 species of nitrogen-fixing bacteria (NFB) and phosphate-solubilizing bacteria (PSB) belonging to Proteobacteria, Firmicutes, Actinobacteria and Cyanobacteria were detected, and the FH treatment increased the abundance of NFB and PSB of Firmicutes in the soil significantly. The linear regression analysis also demonstrated that the β-diversity of NFB and PSB of Firmicutes was significantly correlated with the AN/TN ratio in the soils ($p< 0.05$). Moreover, there was a significant positive correlation between the β-diversity of PSB of Proteobacteria and celery yield, whereas there was a significant negative correlation between the β-diversity of PSB of Firmicutes and incidence of sclerotinia rot. The spearman correlation analysis also indicated that the abundance of *Brevibacillus composti* and *Priestia flexa* belonging to PSB were significantly positively correlated with AP/TP ratio ($p< 0.05$). Likewise, the abundance of *Bacillus subtilis*, *Paenibacillus castaneae*, *Calothrixsp.PCC7103*, and *Tolypothrix tenuis* belonging to NFB were significantly positively correlated with AN/TN ratio ($p< 0.05$). Furthermore, the abundance of *Bacillus sp. BA3*, *Bacillus sp. ISL-4*, *Peribacillus butanolivorans*, and *Clostridium sp.* belonging to NFB or PSB were significantly positively correlated with the celery yield ($p< 0.05$), and significantly negatively with the incidence of sclerotinia rot ($p< 0.05$). The results fully suggest that spraying 2% of the ferment solution manufactured from discarded leaves improves microbial diversity, increases the abundance of NFB and PSB, and elevates the content of available N and P in the soil significantly, and reduces the incidence of sclerotinia rot in celery plants, thereby increasing the celery yield significantly. The application of the ferment solution produced from discarded vegetable leaves improves soil fertility, reduces incidence of crop disease and pests, increases crop yield, and thus can partially replace chemical fertilizers and pesticides. This method establishes an effective and simple way for recycling agricultural wastes.

# Study on Spatial Distribution Characteristics of Soil Organic Matter in Tea Gardens of Laoshan District, Qingdao Based on GIS and the Impact of Different Altitudes

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**ABSTRACT**

The evaluation of soil fertility in tea gardens has received growing attention in recent years. Taking the tea gardens in Laoshan District as the research area, this study collected 412 soil samples to determine the content of soil organic matter. Combined with geostatistical methods, the relationships among spatial distribution characteristics, spatial heterogeneity and altitude were analyzed. The results are as follows:

(1) Analysis of soil nutrients in the tea gardens of Laoshan District showed that the content of soil organic matter in the 0 - 20 cm and 20 - 40 cm soil layers ranged from 6.87 to 29.67 g·kg-1 and from 5.93 to 24.09 g·kg-1, respectively. Based on the mean value, the soil fertility was classified as Grade IV according to the Fertility Evaluation Standard of the Second National Soil Survey of China. The soil fertility in the research area needs to be ameliorated, and the content of soil organic matter is at a medium-low or deficient level. It is recommended to increase the application of organic fertilizers in the tea gardens of Laoshan District.

(2) Results of descriptive statistical analysis and semi-variogram analysis indicated that the coefficient of variation of soil organic matter ranged from 19.92% to 201.16% (with an average of 20.28%), which demonstrated that soil organic matter had moderate variability. The nugget effect of soil organic matter in the 0 - 20 cm soil layer of tea gardens in Laoshan District ranged from 25% to 75%, implying that it was affected by both structural and random factors. The semi-variograms of soil organic matter in the 0 - 20 cm and 20 - 40 cm soil layers were both fitted with exponential models, with the coefficients of determination ($R^2$) being 0.985 and 0.857, respectively, which indicated a good fitting effect.

(3) The results of spatial distribution analysis revealed that the content of soil organic matter in the 0 - 20 cm and 20 - 40 cm soil layers exhibited a distribution pattern of being higher in the eastern and southern parts and relatively lower in the western and northern parts of the study area.

(4) Results of correlation analysis and analysis of variance (ANOVA) showed that the content of soil organic matter in both the 0 - 20 cm and 20 - 40 cm soil layers was significantly positively correlated with altitude, with significant differences observed, which indicated that soil organic matter content was affected by altitude.

In conclusion, based on an extensive dataset, this study comprehensively clarified the spatial variability characteristics of soil organic matter in tea gardens of Laoshan District and its relationship with altitude, which provides a scientific basis for further research on the spatial variability of soil fertility and related studies in this area.

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# Effects of repeated application of horse dung manure on the accumulation of the elements in topsoil of paddy fields -A case of newly reclaimed paddy fields in Kyoto University Farm, Japan-

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## ABSTRACT

Paddy fields in Kyoto University Farm in Kyoto, Japan were reclaimed in 2016. Horse dung manure has been applied to the fields since the fiscal year 2016, and rice cultivation has started thereafter. From 2017 to the present, we have collected topsoil samples from six of the paddy fields every spring. Five fields have received the application of horse dung manure almost every year, whereas one field did not. By analyzing the soil and manure samples collected from 2017 to 2024, we demonstrate the relationship between the input of the elements by the application of manure and the accumulation of the elements in topsoil. We also show the form of the elements in soil by applying the size fractionation to the soil samples.

Soil samples were collected by dividing the six fields into 90 plots. In each plot, a soil sample consisting of five subsamples was taken from the plow layer. The samples collected from the same field were mixed to prepare composite samples to be analyzed. Air-dried, 2-mm sieved soil samples (bulk samples) were subjected to the 20 µm-mesh nylon mesh sieving to collect sand fraction samples (sand samples). After dry combustion or wet digestion of the bulk and sand samples, the contents of the six elements (C, N, P, K, Ca and Mg) were measured. The contents of the six elements in the manure samples were also measured. Then, the inputs of the elements by manure application were compared with those of the elements in the bulk and sand samples. Besides the total elemental contents, chemical properties of the bulk samples were analyzed by conventional methods.

Among the six elements measured, the inputs of C, N and P by horse dung manure were quantitatively comparable to their reserves in topsoil. Repeated application of the manure increased the total contents of C, N and P in topsoil. As more than 90% of the manure applied were classified as particulate organic matter by the nylon mesh sieving, manure-derived C, N and P accumulated in topsoil existed mainly in the sand fraction, i.e. particulate organic matter fraction. In contrast, the inputs of K, Ca and Mg by the manure were much smaller than their reserves in topsoil. Repeated application of the manure did not increase the total contents of K, Ca and Mg in topsoil. Besides these results, bulk samples having received manure applications showed higher contents of available N, available P and exchangeable cations (K, Ca and Mg) than those without manure application. However, the contents of exchangeable Ca and Mg in topsoil with manure applications decreased gradually from 2017 to 2024, suggesting their leaching from topsoil.

In conclusion, comparing the input of the elements by manure and their total amount in topsoil was useful to predict which elements will accumulate in soil by repeated application of manure. In our case, the application of horse dung manure was effective for increasing C, N and P in the sand fraction of topsoil and maintaining the availability of N and P in topsoil.

# Biotic and Abiotic Catalytic Strategies for Accelerated Humic Substance Formation

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**ABSTRACT**

Humic substances (HS) are critical for soil fertility and environmental remediation, yet their natural formation requires decades to centuries. This study examines both abiotic and biocatalytic pathways for accelerated HS synthesis through integrated experimental and computational approaches. We investigated graphitic carbon nitride (g- $C_3N_4$) catalysis in promoting hydroquinone (HQ) oxidative polymerization within $MnO_2$ and $Cr_2O_7^{2-}$ systems. As a Lewis base with substantial surface area, g-$C_3N_4$ enhanced metal oxide-polyphenol interactions through π-π stacking, increasing reaction rates 3-6-fold. Electron transfer facilitated by g-$C_3N_4$ proved crucial for in-situ HQ oxidation, producing HS with improved morphology and larger particle sizes. DFT calculations confirmed that g- $C_3N_4$…HQ…metal oxide complexes exhibit higher binding energies and narrower HOMO-LUMO gaps than binary systems, explaining enhanced kinetics. $^{13}C$ NMR spectra validated predicted HS structures. Building upon these insights, we developed a microbial-mineral catalytic strategy enabling rapid HS formation within 15 days through coupled Saccharomyces cerevisiae fermentation and $MnO_2$ catalysis. Systematic comparison of microbial systems revealed a dual-pathway humification mechanism characterized by UV-Vis, FTIR, XRD, SEM, XPS, $^{13}C$ NMR, and DFT analyses. $MnO_2$ preferentially catalyzed aromatic condensation (30-45% carbon) via surface-mediated radical coupling, while microbial metabolism promoted aliphatic carbon formation (50-60%). The S. cerevisiae-$MnO_2$ system achieved optimal balance (~55% aliphatic, ~35% aromatic), producing hierarchical structures resembling natural humic acids with extended visible-light absorption (≤450 nm), moderate $E_4/E_6$ ratios (3-4), and π-π stacking distances of ~4.0 Å. DFT calculations demonstrated $MnO_2$-facilitated electronic activation with 82% HOMO-LUMO gap reduction and nine-fold binding energy increase (111.13 kcal $mol^{-1}$). This work establishes a mechanistic framework integrating abiotic and biocatalytic approaches for tunable, rapid HS synthesis with environmental applications.

**Keywords**

Humification; Biocatalysis; Metal oxide catalysis; g-$C_3N_4$; Polyphenol polymerization

# Global Potential Effects Analysis of Biochar on Crop Yields and Soil Quality

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**ABSTRACT**

Biochar has been widely used for soil improvement, but uncertain results persist due to diverse biochar characteristics, soil properties, and crop responses. Therefore, the effects of biochar on crop yields and soil quality were evaluated using effect sizes from 1011 paired data points from field trials, based on a global meta-analysis method. The results indicated that biochar with a higher total phosphorus concentration (≥1.0%), total carbon concentration (≥70%), specific surface area (≥50 m2 $g^{-1}$), and biochar application rates of 10–30 t $ha^{-1}$ are optimal for improving crop yields. Biochar made from manure (effect size, 42%) exceeded that made from ligneous (22%) or cereal (12%) material. Porous, acidic, or young soil types are optimal for biochar application, while sandy and clay soils are preferred over loam soil. Soils with lower available nitrogen (<80 mg $kg^{-1}$), phosphorus (<10 mg $kg^{-1}$), potassium (<120 mg $kg^{-1}$), pH (<4.5), and cation exchange capacity (<10 cmol $kg^{-1}$) were more effective. The effect of biochar on yield is higher for cash crops (oil plants: 37%, vegetables: 28%) compared to food crops (legumes: 26%, maize: 20%, wheat: 12%), with no significant effect observed on rice. Finally, biochar increases crop yields by improving soil quality through enhanced levels of soil organic carbon, total nitrogen, ammonium-nitrogen, nitrate-nitrogen, and soil pH while reducing soil bulk density. Our research enhances understanding of the relationships between biochar, soil, and crops, aiding researchers, manufacturers, and farmers in making informed decisions regarding biochar selection, planting locations, and crop choices. However, it remains unclear to what extent machine learning can accurately predict crop yield or SOC when biochar is applied to soil. In our study, Random Forest (RF) and Multilayer Perceptron Neural Network (MLP- NN) models were employed to predict crop yield and SOC with 297 paired data from field trials. The results indicated that the RF model (test $R^2$ = 0.83) did not differ significantly from the MLP- NN model (test $R^2$ = 0.84) in predicting crop yield. However, the RF model (test $R^2$ = 0.87) performs significantly better than the MLP- NN model (test $R^2$ = 0.53) in predicting SOC. The most influential features for crop yield were found to be the biochar application rate (15%), initial SOC (13%), biochar pH (10%), and biochar TP (10%). In contrast, the variation of SOC was primarily influenced by latitude (26%), biochar application rate (22%), initial SOC (15%), and biochar pH (13%). Furthermore, both crop yield and SOC variation were influenced by multiple factors, not solely one, and their impacts were not necessarily linear. This study suggests that the optimization of biochar pH and phosphorus content, along with the regulation of its application rate in sandy or clay- rich soils, can simultaneously enhance both crop yield and SOC. In the future, we hope to develop a decision support system with prediction, different scenarios, and consultation capabilities based on geospatial location.

**Keywords:** biochar, crop yield, soil organic carbon, Multilayer Perceptron Neural Network, Random Forest

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# Revalorization of spent coffee ground as peat alternative for soilless culture

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**ABSTRACT**

Peat is a nonrenewable resource that we are using at alarming rates. Development of peat alternative from organic waste could be a cost- and environment-friendly way of disposal. Biochar, which is usually made from thermochemical conversion of organic waste, may partially replace peat during soilless culture, but the high cost for biochar preparation limits its widespread application. We recently developed a torrefaction process that uses the superheated steam (SHS) as the carrier gas and heat transfer medium. Such technology is a more efficient and economical way to produce biochar. Therefore, this study evaluated the potential of SHS torrefied spent coffee ground (SCG), which is a major biowaste of the coffee industry, as a peat alternative. Results indicate that SHS torrefaction at 300℃ for 30 min could effectively eliminate the phytotoxicity of SCG. When peat is replaced by SHS-torrefied SCG for up to 20% (v/v), lettuce yield was maintained or slightly improved relative to pure peat. The content of Chlorophyll a and b in leaf also increased following the addition of SHS-torrefied SCG. The presence of SHS-torrefied SCG in growing substrate also significantly improved lettuce quality attributes such as the content of soluble sugar, soluble protein, polyphenols, and flavonoids, whereas nitrate content in leaf notably decreased. In conclusion, SHS torrefaction could effectively transform SCG into a peat alternative. The SHS torrefied SCG may replace peat for up to 20% (v/v) in lettuce culture without yield or quality penalty.

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# Integrated Assessment of Soil Water-Storing Function across Australia: A Multi-Dimensional Approach to Mapping Soil Security

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**ABSTRACT**

The concept of soil security provides a comprehensive framework for assessing the status and vulnerability of soil functions. This study evaluates the security of the soil water-storing function across Australia by integrating all five dimensions of soil security: capacity, condition, capital, connectivity, and codification. We present a multi-criteria approach that combines biophysical, socio-economic, and regulatory factors to deliver a holistic assessment of soil security. Using the pedogenon concept and the Technique for Order PReferences by Similarity to Ideal Solution (TOPSIS), we ranked soil insecurity across defined soil "districts" treated as management zones.

Indicators of soil water-storing function included raster maps (90 m resolution) of available water capacity (AWC) and soil thermal inertia for the top one metre. Normalised average utility scores of these indicators per genosoils was used to represent soil capacity and phenosoil deviations from genosoils as condition. Soil capital (economic value) was assessed based on a linear regression analysis between water holding capacity and farm price. To capture connectivity, we integrated a map of farmers' awareness of this soil function, derived from interviews and a separate study. Codification was assessed through the presence or absence of federal and state legislation explicitly supporting soil water-storing function protection. All indicators were spatially intersected with soil districts map, then, a decision matrix of scores of each dimension for each district was created to calculate the closeness to ideal scores (using TOPSIS). Finally, each district was ranked based on multi-dimensional vulnerability to water loss. The resulting soil security map identifies zones requiring targeted intervention based on their combined biophysical, socio-economic, and regulatory risks. In addition, the most restricting dimension and degree of restrictiveness was calculated for strategic management and planning. This study demonstrates a practical application of the soil security assessment framework for comprehensive soil protection, enabling identification of where and which dimensions of soil security are most at risk.

**Keywords:** soil security, soil functions, soil management, land use planning

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# Study on the Suitability Evaluation and Spatial Zoning of Soil Fertility Enhancement Technologies for Different Cropland Types in Yuanmou County, Yunnan Province, China

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## ABSTRACT

The dry-hot valley region of southwestern China is characterized by extremely high temperatures, intense evapotranspiration, and highly fragmented terrain, conditions that lead to severe soil erosion, nutrient deficiency, poor tillage conditions, and generally low soil fertility. These factors substantially constrain the sustainable development of regional agriculture. The rational allocation and regionalized promotion of soil fertility enhancement technologies are therefore essential for achieving efficient agricultural utilization and ecological conservation in dry-hot valleys. However, existing studies have predominantly focused on single crops or small-scale field experiments and lack systematic analyses of technology suitability across multiple farmland types at the regional scale, making it difficult to support precise technology deployment under the complex ecological background of dry-hot valleys. To address this gap, this study takes Yuanmou County in Yunnan Province, China, as the research area. Using multisource spatial data, we identify three typical farmland types in the region: sloping farmland, flat farmland, and newly reclaimed farmland. Based on the ecological characteristics of dry-hot valleys and the distinct constraint factors associated with each farmland type, we conduct suitability evaluation and spatial zoning for the existing soil fertility enhancement technologies matched to these farmland types. The evaluation framework is constructed from three dimensions—soil fertility, economic benefits, and key constraint indicators specific to each farmland type—and a combined weighting method is applied to determine the weights of the evaluation indicators, thereby ensuring the scientific quantification of the index system. Through spatialization of indicators and calculation of a comprehensive suitability index, the study aims to generate spatial suitability zoning outcomes for soil fertility enhancement technologies in the dry-hot valley region. Furthermore, multi-scenario simulations are performed to compare different technology-combination scenarios, revealing spatial differences and comprehensive effects, and exploring optimal pathways for regional soil fertility improvement. Overall, this research establishes a differentiated suitability evaluation system tailored to the ecological context of dry-hot valleys, elucidates the spatial distribution patterns and influencing mechanisms of technology suitability among different farmland types, and provides important theoretical support and practical guidance for regional agricultural sustainability and the scientific promotion of soil fertility enhancement technologies.

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# Preliminary Study on a Method for Evaluating the Basic Soil Fertility of Medium and Low-Yielding Land in Anhui Province Based on Natural Soil Properties

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**ABSTRACT**

Enhancing the fertility of medium and low-yielding land can provide a crucial guarantee for increasing regional grain production. Anhui Province is a major agricultural and grain-producing province. Identifying the natural attributes, types of constraints, affected areas, and spatial distribution of medium and low-yielding land is the prerequisite and foundation for its transformation. This study is based on the findings of the Second National Soil Survey (Soil Gazetteer of Counties in Anhui Province), the National Type Division and Improvement Technology for Medium and Low Yield Fields (NYT310-1996), and the Cultivated Land Quality Grade(GB/T 33469-2016).It analyzes the natural attributes of soils in Anhui Province, constructs an indicator system for identifying constraints in medium and low-yielding land, and uses the overlaid patches of soil maps from the Second National Soil Survey period and cultivated land from the 1980 land use in Anhui as evaluation units. This method identifies different types of constraints in medium and low-yielding land, establishes a distribution map of such farmland in Anhui Province, and clarifies their spatial distribution patterns. Finally, through analysis of soil samples collected in Lingbi County and Fengyang County in 2025, the accuracy of the distribution of medium and low-yielding land was verified. The results indicate that (1) Anhui Province's medium and low-yielding land encompasses 15 soil types, 520 soil species, 4 types of impediments, and 14 impediment factors, with structural impediments covering the largest proportion of the area (29.82%). (2) In terms of spatial distribution, medium and low-yielding land occupies a larger area in the northern and southern regions, with the primary constraints being six factors: leakage, retention, soil erosion, low in soil organic matter, low in available P and K. (3) The province has approximately 4.77 million hectares of medium and low-yielding land, accounting for 61.25% of its total arable land area. (4) In both 1985 and 2017, there was a highly significant negative correlation ($P<0.001$) between the proportion of medium and low-yielding land across counties in Anhui Province and grain yield per unit area. The findings can provide scientific data support for Anhui Province's exploration of transforming medium and low-yielding land and enhancing agricultural productivity.

**Keywords:** medium and low-yielding land; physical soil property; evaluation method; soil constraint factor; Anhui Province

This paper defines medium and low-yielding land as cultivated land where one or more types of soil impediments-including structural type, chemical type, fertility type, soil horizon type, and environmental type - result in low natural soil fertility levels, relatively low and unstable yields.

# An interactive land suitability tool for Queensland, Australia

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**ABSTRACT**

An on-line crop suitability tool (CropSuit*) has been developed for Queensland, Australia. The tool automatically draws on available spatial data to produce visual crop suitability outputs. It operates consistently across the state, highlighting areas that are potentially suitable for specific crops in terms of climate, soil and land attributes.

The tool is the culmination of several attempts to make land suitability information in Queensland more transparent and accessible, involving collaboration between different government departments. It meets a recognised need for increased access to land evaluation information to inform decision making, especially at the pre-feasibility stage where land development, diversification or intensification is being investigated.

The derived spatial attributes are matched against crop growth requirements and assessed as limitations in a traditional FAO style land evaluation framework. The tool operates at various scales – at a regional level, climate factors and slope are the only attributes considered, and the areas are broadly assessed as being suitable or unsuitable. As the user drills down, more soil and land attributes are included. When zooming in to the local level (<1,000 ha), results are displayed in five suitability classes for each of the available crops.

The soil and landscape attributes driving the suitability assessments are drawn from Queensland's Soil and Land Information (SALI) database, other statewide datasets and in some cases from the Soil and Landscape Grid of Australia. The variability of the spatial data is assessed by averaging the attributes for 1600 gridded points within the area selected – displaying the mean, median and standard deviation for attributes where the data is numerical, and a percentage for categorical data.

The reliability of the soil data utilised to produce the outputs depends on the intensity of the underlying soil mapping, which varies significantly across the state. The outputs generated are predictions only – it is recommended that detailed on-ground soil and land investigations be conducted prior to making investments at the property level.

The suitability results are displayed as a mosaic of cells – the size of which depends on the dimensions of the selected area. By clicking on a cell, the attributes for that cell, along with a suitability rating for each limitation are displayed. The user can therefore see immediately why a particular parcel of land may be considered unsuitable for a crop, and which attributes are responsible.

The user has the option of overriding the automatically derived spatial data if more accurate information is available, which the tool then utilises to modify the suitability outputs. The ruleset that determines the suitability results is flexible and can be refined over time, while additional limitations and crops may be incorporated.

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*CropSuit – Statewide Suitability tool for Queensland: https://cropsuit.information.qld.gov.au/

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# WRB-Harmonised Soil Mapping to Support Sustainable Land Use Planning in Mediterranean Regions

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## ABSTRACT

Harmonised soil information and land evaluation frameworks are essential for sustainable land management and adequate policy development. Understanding land capability is fundamental for supporting productive agriculture and forestry while minimising the risk of land degradation.

In mainland Portugal, soil mapping has been recently updated and harmonised at 1:100,000 scale using the WRB system. This was achieved by reinterpreting 1:25,000-scale legacy soil maps, in which most soil units were either uncharacterised or incompletely described according to WRB rules, lacking key soil property data. Accordingly, legacy soil data were integrated with land units delineated based on biophysical factors (climate, lithology, and relief). The resulting soil mapping units achieved 76–82% correspondence with legacy profiles under two validation scenarios, confirming the robustness of the proposed methodological framework. The approach enabled the identification of key functional properties and limitations associated with climate and topography, providing a basis for characterising land characteristics and qualities.

The present study contributes to the development of a harmonised land capability map for mainland Portugal under Mediterranean climatic conditions. Major limiting factors include temperature regime, slope angle, rooting depth, fertility, toxicity, soil aeration, water deficit period, erosion risk, carbonate and soluble salt content, terraces, and the proportion of rock outcrops. A hierarchical system was defined to classify each land characteristic or quality into four land capability classes for generic agricultural and forestry purposes, based on minimum class requirements. Subclasses were also identified within each class, according to dominant land limitation(s). Validation through a comparison with the national Land Use/Cover Map confirmed high spatial consistency between predicted capability classes and actual land use.

This integrated framework illustrates how digital soil mapping (DSM) products can underpin evidence-based digital soil assessment (DSA) and guide land-use policy, natural resource management, and spatial planning. The methodology is reproducible, scalable, and adaptable to other Mediterranean or similar environments, thereby bridging the gap between soil mapping and practical applications for stakeholders and policymakers. By providing harmonised and interpretable soil data, this approach supports sustainable land management, optimises productivity, safeguards environmental quality, and contributes to long-term food security.

# Spatial heterogeneity and driving factors of five global arable land datasets in China under a ‘single cropland map’ framework

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**ABSTRACT**

Accurate and harmonized cropland information is a prerequisite for national land spatial planning, cropland protection red lines, and the construction of a unified ‘single cropland map’ in China. In recent decades, rapid advances in remote sensing have produced numerous global and national land use/land cover (LULC) products, but their heterogeneous classification schemes make it difficult to consistently evaluate cropland accuracy and spatial heterogeneity. In this study, we assessed five mainstream cropland products—CACD, CLCD, GLC_FCS30D, WorldCover V200 and ESRI 10 m—after harmonizing them to the FAO “arable-only” definition and a common 30 m area framework. Spatial heterogeneity among products was evaluated from three perspectives: (1) agreement levels used to map cropland heterogeneity at 30 m; (2) provincial-scale agreement with official cropland statistics; and (3) pixel-level accuracy based on a strict leave-one-out References. We further analyzed agricultural climatic zones, a county-level cropland fragmentation index and multiple environmental factors using an XGBoost–SHAP model to identify the main drivers of minimal agreement. Cropland heterogeneity is generally higher in the west than in the east, and higher in mountainous and plateau regions than on plains; humid subtropical hilly regions, the Tibetan Plateau and arid agro-pastoral ecotones emerge as high-risk areas for constructing a consistent base map. CLCD and CACD show the most reliable area and pixel-level performance, GLC_FCS30D is intermediate, while WorldCover V200 and ESRI 10 m exhibit substantial regional biases. Fragmentation emerges as the dominant driver of high heterogeneity, followed by elevation, temperature and slope. These results provide a single-map–oriented basis for selecting and combining cropland products in different regions to support cropland regulation and food security assessment in China.

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# Background concentration and range of potentially toxic elements in Lebanese soils for land suitability assessment

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**ABSTRACT**

Land use planning is a crucial factor of land governance and food security. Land suitability for agricultural production must be linked with soil quality. Soil with potentially toxic elements (PTEs) is one of major concerns because they jeopardize the implementation of SDGs (FAO and UNEP, 2021), contaminate agricultural products and threatens public health (Reis et al., 2025). This work aims at assessing the status of soil pollution in Lebanon as prelude to soil quality predefining the suitability for crop production. This ranges from multifunctional land use in soils with PTEs around the natural background concentration to restricted cropping pattern consisting of technical crops, fruit trees and agroforestry in soils with increasing concentration of PTEs. Based on relatively low soil organic matter content varying between 1% and 3% (Darwish and Fadel, 2017), the suitability for specific type of crops in linked in this study with two factors, PTEs content and soil texture. While the trigger threshold for Cr in clay soil is 100 mg $kg^{-1}$, it decreases to 60 mg $kg^{-1}$ in loamy and silty soil (Carlon, 2007). The results of soil analysis revealed 76.3% and 74.3% of studied soils above the natural background value for Cr and Ni (50 mg $kg^{-1}$ to 40 mg $kg^{-1}$), respectively (Figure 1).

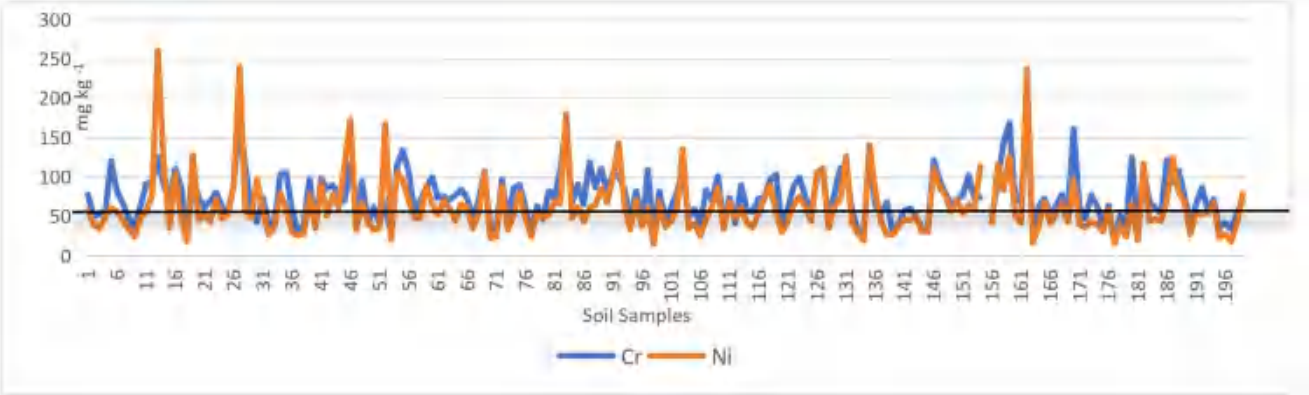



Figure 1. Cr and Ni abundance in selected Lebanese soils (196 soil samples)

The concentration of As and Pb in the root zone showed only 2 soils (1.01%) to exceed the multifunctional land use (20 mg $kg^{-1}$ and 100 mg $kg^{-1}$) for As and Pb, respectively. The content of Cd and Hg was within the permissible level. The geospatial distribution of problematic PTEs will be linked to soil texture and compared in GIS tools with current land occupation to provide recommendations for alternative agricultural and nonagricultural land uses.

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# Long-term soil multifunctionality under climate trajectories, land-use transitions, and management practices

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**ABSTRACT**

Soils are pivotal to the sustainable provision of a wide range of ecosystem services (SES), including provisioning services (food, water, energy), regulating services (water and air quality, detoxification, etc.) and cultural services. However, the medium- and long-term trajectories of these services under climate change, land-use shifts, and management practices remain poorly documented and therefore still not being fully taken into account in land use planning. The objective of this study was to analyse the joint spatial and temporal changes in a set of ecosystem services provided by soils in two territories that contrast in terms of soil types and socio-economic development. This was realised through the integration of scenario analysis and dynamic modelling.

*Study areas*

The first study area is the 12 km² Kervidy-Naizin watershed (Brittany, France) with a high concentration of livestock, along with major crops of maize, wheat, and both temporary and permanent grasslands. The anticipated evolution of this territory is a transition from intensive agricultural production systems to multifunctional agroecological systems with reduced environmental impacts. The second site is the Saclay Plateau (southwest of Paris), a historically agricultural area of 25 km² under strong urbanization pressure since the 1980s. Land-use categories considered include arable land, grassland, impervious urban areas, and non-impervious urban areas (gardens, parks, simulated as grassland).

*Methods*

The simulations encompassed the period 1991–2050 for Kervidy-Naizin and 1982–2050 for Saclay. Both studies appraised five ES (crop water supply, crop nitrogen supply, carbon sequestration, water quantity regulation, water quality regulation) and biomass production. Climate scenarios (RCP 4.5 and RCP 8.5) and land management scenarios (business-as-usual, European Green Deal, organic farming, energy cropping) were tested in Kervidy-Naizin. Meanwhile, Saclay focused on the combined effects of climate change and land-use transitions.

*Results*

In Kervidy-Naizin, ES provision proved highly sensitive to climate, management, and soil properties (e.g., soil depth). Some services responded synergistically, while others showed trade-offs, highlighting the importance of considering bundles of ES and their interactions.

In Saclay, climate and land-use changes often acted synergistically to reduce SES provision. However, non-impervious urban spaces played a buffering role, mitigating service losses. Responses varied across soil types and services, emphasizing spatial heterogeneity.

*Conclusions*

Collectively, these case studies demonstrate the interactions between climate trajectories, land-use dynamics, and management practices to shape soil-based ecosystem services. They highlight the need to consider multiple services simultaneously, account for synergies and trade-offs, and integrate soil diversity into long-term strategies for sustainable land management and territorial planning.

# Relationships among cultivated land quality, crop yield and economic benefit based on a long-term field experiment with different fertilization and mulching treatments

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**ABSTRACT**

Clarifying the definite relationship among soil quality, crop yields and economic benefits is of great significance for the rational management of soil quality. A 34-year long-term mulching and fertilization positioning experiment station of Shenyang Agricultural University was used due to the advantages of long-term positioning experiments over 30 years, such as the stable differences in soil quality between different treatments, the controllable and accurate acquisition of evaluation indicators, and the full-process management and economic benefit accounting., 14 treatments including mulching (F) and non-mulching (WF) with single nitrogen application (N2, N4), single organic fertilizer application (M2, M4), combined organic and inorganic fertilizer application (M1N1, M2N2), and no fertilization control (CK) were selected. According to the current national standard of China, "Soil Quality Classification", soil indicators were tested and soil quality was evaluated for different treatments by calculating the comprehensive index of soil quality (*IFI*). The economic benefit was accounted by the input-output data from farmland management, and the relationship between soil quality, crop yield and economic benefit were examined. The results showed, (1) The application of organic fertilizer can stabilize soil pH and increase soil nutrient content, thereby improving soil quality. The treatment with the highest soil quality was WF-M4 treatment, which was 6.78% higher than WF-CK. Single nitrogen application can reduce soil pH and soil nutrient content, leading to a decline in soil quality. The treatment with the lowest soil quality was WF-N4, which was 5.22% lower than WF-CK. (2) Fertilization can effectively increase yield. Under non-mulching conditions, the WF-M4 treatment had the highest yield, which was 161.51% higher than WF-CK. Under mulching conditions, the treatment with the highest yield was F-M2N2, which was 92.55% higher than F-CK. (3) Under single nitrogen application, *IFI* was negatively correlated with yield. The application of organic fertilizer made *IFI* positively correlated with yield. Under single nitrogen application, when the soil quality grade decreased by one level, the yield of non-mulching treatment could increase by 1.84 t $hm^{-2}$, and the yield of mulching treatment could increase by 2.32 t $hm^{-2}$. Under the addition of organic fertilizer, when the soil quality grade increased by one level, the yield of non-mulching treatment could increase by 3.62 t $hm^{-2}$, and the yield of mulching treatment could increase by 3.75 t $hm^{-2}$. (4) Under single nitrogen application, *IFI* was negatively correlated with economic benefit. The application of organic fertilizer led to an optimal combination relationship between *IFI* and economic benefit. Under mulching conditions, the combined application of organic and inorganic fertilizers led to a double-win situation for soil quality and economic benefit. Under single nitrogen application, when *IFI* decreased by 0.01, economic benefit could increase by CNY 1758 to 2717 $hm^{-2}$. Under the addition of organic fertilizer, when *IFI* reached 0.7947 under non-mulching conditions, the economic benefit was the largest, at CNY 13282 $hm^{-2}$. Under mulching conditions, when *IFI* reached 0.7427, the economic benefit was the largest, at CNY 10280 $hm^{-2}$. When *IFI* reached 0.7926, the economic benefit was the largest, at CNY 2678 $hm^{-2}$. (5) The WF-M4 treatment achieved the highest soil quality and the highest yield. The WF-M1N1treatment had the highest economic benefit. That is, under the condition of no mulching, the application of organic fertilizer can enhance soil quality, crop yield and economic benefit simultaneously. In the mulching treatments, to maintain or improve soil quality, the treatment of F-M1N1 or F-M2N2 is required, which can achieve a triple-win situation in terms of soil quality, crop yield and economic benefit.

# Interpretable machine learning models analyze the mechanism of nutrient evolution in red soils of Jiangxi under the dual drivers of climate and social economy

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**ABSTRACT**

Understanding the spatial variability and driving mechanisms of soil nutrients is critical for sustainable agricultural management in the red soil region of Southern China. However, decoupling the complex interactions between natural environmental factors and intensifying socioeconomic activities remains a challenge. This study focuses on Ji'an City, a typical red soil area, to predict the spatial distribution of six key soil properties—pH, base saturation (BS), soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and total potassium (TK)—and to unravel their driving forces. We developed an interpretable machine learning framework by integrating multi-source data (climate, topography, vegetation, and socioeconomic indicators) with the SHapley Additive exPlanations (SHAP) approach. The results demonstrated that the optimized machine learning models achieved robust predictive performance, with coefficients of determination ($R^2$) ranging from 0.62 to 0.85 for the validation datasets. The SHAP analysis revealed that the spatial evolution of soil nutrients is governed by a dual-drive mechanism involving both climate change and socioeconomic development. Specifically, SOC were primarily controlled by climatic factors such as mean annual temperature, exhibiting strong zonal characteristics. In contrast, TP, TK, and pH were more sensitive to socioeconomic drivers, such as fertilizer application rates, reflecting the dominant footprint of anthropogenic management. Furthermore, the study identified significant non-linear threshold effects; for instance, SOC levels decreased sharply when temperature exceeded 2°C. These findings overcome the "black box" limitation of traditional modeling and provide a mechanistic basis for site-specific soil management. The study suggests that policy interventions for soil acidification and nutrient balancing in Ji'an City must account for the spatial heterogeneity driven by these coupled climate-socioeconomic forces.

# Soil–Geochemical Controls of NDVI Seasonality in Steppe ecosystems of the Turano–Uyuk Intramontane Depression (Tuva, South Siberia)

**ABSTRACT**

In steppe landscapes under a sharply continental climate, the annual course of the phytoproductive process is governed by soil water regime and nutrients availability / However the contribution of soil–geochemical conditions to intra-seasonal phytomass dynamics remains poorly quantified. This study aims at identifying relationships between moisture regime types, soil properties and the annual course of green phytomass in landscape units of the Turano–Uyuk intramontane depression (Tuva, South Siberia). We tested the hypotheses that (1) the temporal pattern the annual NDVI fluctuations reflects the type of moisture regime and nutrient availability, and (2) combined NDVI and soil–geochemical characteristics can be used to infer the structure of radial and lateral fluxes of water and dissolved substances.

For May–September 1990–2024, NDVI time series were derived from Landsat imagery and smoothed using locally weighted regression (LOWESS) with day of year as the temporal coordinate. We tested whether NDVI fluctuations were related to temperature and precipitation variability measured at nearby meteorological stations. Hydrothermal anomalies were extracted using STL decomposition. In Google Earth Engine, VCI, NDVI derivatives and the Greenest Day of the Year were additionally calculated. In 2024–2025, 31 field sites representing major landscape types were surveyed: landscape descriptions, measurements of green phytomass and litter, and soil sampling from humus horizons were carried out. Soils were classified according to the Russian Soil Classification (2004), and standard physical and chemical analyses were performed.

Five groups of landscape units differing in the combination of water regime and soil–geochemical properties were identified ranging from eluvial xerophytic steppes on cryoarid soils to superaquatic halophytic communities on dark and gleyic solonchaks. Xerophytic and mesoxerophytic steppes exhibit a bimodal annual NDVI pattern (with early July and mid-August peaks) with an intermediate decline and maximum interannual variability in late July; they also show an early-summer delay or short-term decrease in green phytomass, coinciding with low snow water storage and rapid desiccation of light loamy cryoarid soils. Hydromorphic floodplain units and groundwater discharge zones are characterized by later, typically single summer NDVI peaks and reduced interannual variability. In halomorphic superaquatic units with sulfate–magnesium–sodium and chloride–carbonate–sodium salinity and high contents of nitrate nitrogen, available potassium, gypsum and sulfates, NDVI displays the most prolonged summer increase and minimal response to interannual hydrothermal fluctuations.

The results support the hypothesis that the annual NDVI curve is a useful diagnostic indicator of water regime type and nutrient availability in steppe landscape units. The interpretation of the identified sequence as reflecting gradients of radial and lateral water and solute fluxes is consistent with NDVI and soil–geochemical patterns, but remains a working hypothesis that requires direct measurements of water and salt fluxes.

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# Soil multifunctionality assessment in Grenoble Alpes metropolis using the MUSE method for sustainable land use planning

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**ABSTRACT**

Soil multifunctionality reflects the capacity of the soil to provide multiple ecosystem functions and services (Garland et al., 2021). It isjointly determined by biotic and abiotic factors(Y. Shi et al., 2025).The MUSE method-originally a French acronym for Method for the Evaluation of Soil Multifunctionality-is a Digital Soil Mapping (DSM) approach that evaluates-scoresfour soil ecological functions: carbon storage, biodiversity storage, infiltration capacity, and agronomic potential(Branchu et al., 2021). These functions are assessed individually and in combination through a scoring system that enables the spatialization of results and the evaluation of soil multifunctionality.The scoring system allowsalsoguidanceof soil management practices by promotinginformed decision-making aimed at preserving soil functions.

The EU-funded Horizon Europe SPADES(Spatial Planning and Design with Soil)project aims to integrate soil health into spatial planning and design. By promoting soil literacy and gatheringadaptable tools, methods and instrumentsamong thecountries involved inthe project, SPADESis putting soil health at the heart of planning for the benefit of current and future generations.Grenoble-Alpes Metropolis(GAM)isone of 17 SPADES research pilots that form the core of cocreation to learn, develop and test transferableresults-recommendationsregarding soilhealth integration in spatial planning and design.(For further information, see the SPADES project website: Home | SPADES).

Grenoble-Alpes Metropolisisinsoutheastern France, nestled in a valley surrounded by the Alps.Its territory includes a unique combination of dense urban centers, agricultural lowlands, forested hills, and mountainous natural parks, which creates a mosaic of landscapes with distinct soil characteristics and functions. GAM is experiencing urban sprawl, habitat fragmentation, and soil degradation due to construction, infrastructure development, and intensive land use. Soil sealing and compaction are common in peri-urban and commercial areas, while agricultural soils face risks of erosion and conversion. These trends threaten the ecological, agricultural, and climate-regulating functions of soils(For further information, see the SPADES project website: Home | SPADES).Moreover, while the region is environmentally ambitious, integrating soil data and soil health into spatial planning frameworks remains a complex task. Local planning documentsoften lack detailed or accessible soil information, limiting the capacity of planners to make informed, soil-sensitive decisions.

Within the framework ofSPADES project, this study aims to testthe MUSE method at the Grenoble-Alpes Metropolispilot site toassess soil multifunctionality and support soil-informed land-use planning.The outcomesof the study willeventually(ii) helpintegrating soil intelligence into decision-making processes, the approach seeks to guide soil management practices that preserve soil functions, improve soil quality, and promote sustainable land use. As a SPADES pilot territory, Grenoble-Alpes Metropolisintends to operationalize this soil-smart approach in local planning instruments, particularly through the revision of key planning documents, ensuring that soil functions, and sustainability criteria are explicitly considered. (ii) Supportthe development of an improved access to soil data for planners, positioning Grenoble-Alpes Metropolisas a model for soil-conscious territorial planning.

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# Assessing the Physico-Chemical Properties and Fertility Status of Selected South African Wetland Soils Using XRF, SEM, and Soil Fertility Index

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**ABSTRACT**

Soil fertility status and the inherent quality indices provide fundamental information on the appropriate management strategy required to support crop growth, increase agricultural productivity, and guarantee food security. This study evaluated the physico-chemical features of four selected wetlands in the North West Province of South Africa. Thirteen geo-Referencesd soil profiles were dug in the study areas, and described according to the FAO guidelines for profile description, followed by soil sample collection for various determinations. The soil fertility status was subsequently assessed using X-ray fluorescence (XRF), scanning electron microscopy (SEM), and soil fertility index (SFI). The highest sand, silt, and clay contents were recorded in Pilanesberg Kgama, Mahikeng, and Klerksdorp, respectively. The bulk density of the surface and subsurface soil horizons across all profiles ranged from 1.16 to 1.30 g/cm$^3$ and was statistically comparable. The moisture content ranged from 3.96 to 25.87% (mean=12.75%; CV=54.59%). The mean infiltration rate ranged from 7.58 to 11.83 mm/hr (mean= 9.37 mm/hr; CV=21.1 mm/hr). Soil porosity ranged between 51.19 and 64.00% (mean=56.88%; CV=6.21%) while the silt/clay ratio ranged from 0.34 to 1.09 (mean=0.62; CV=61.96%). Analysis of variance results revealed a significant ($p \leq 0.05$) variation in the silt/clay ratio among the different profiles. Soil pH ($H_2O$ and KCl) across the different horizons ranged from 6.56 to 10.28, indicating slightly acidic to very strongly alkaline. Soil organic matter levels ranged from 0.29 to 7.73% across different soil depths, with decreasing concentrations at lower soil depths. A slightly elevated total N content was observed in the surface horizons with higher available P levels in the surface horizons (range: 0.09 to 55 mg/kg) than the subsurface horizons (range: 0.04 to 49.50 mg/kg) in the respective profiles, mostly at Mahikeng and Potchefstroom. The concentration of extractable micronutrients in all examined profiles was in the order of Mn> Fe>Mo>Cu>Ni>Zn>Cr. The correlation analysis of soil chemical properties revealed that organic matter has a highly significant correlation with total N, a moderately significant correlation with K and Ca, but a negative correlation with Mg, while it showed a highly significant correlation with the C: N ratio. The XRF results revealed the preponderance of P, K, Ca, Mg, S, Cl, and Mn, with fewer Na in key profiles across the different sites, while the SEM images showed that soil samples were mostly characterised by fragments and agglomeration of compacted soil layers, indicating leaching losses within the different horizons of these wetlands. The soils' physical and chemical properties revealed significant potential for wetland soils to support sustainable agricultural production with best management practices.

**Keywords:** Soil fertility index, Food Security, Soil productivity, XRF, SEM, Wetlands, Coefficient of variation.

# Soil Under Stress: Climate Change, Water Dynamics and Agricultural Resilience in Finland

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## ABSTRACT

Climate change is reshaping Nordic climate, altering both temperature and precipitation patterns. Winters are no longer able to maintain stable snow cover, which leads to dry springs, while summers bring heavier rainfall and extended heatwaves. These shifts are disrupting the delicate soil-water balance, putting crop production in Finland under increasing pressure. Different soil types respond very differently to these changes: clay soils are prone to surface flooding, while sandy soils struggle to retain water and rely on groundwater that is often too deep for plants to access. This research is part of the Water and Food Futures project, under Strategic Research Council's Water for Welfare, Security and Peace program. Our goal is to provide robust evidence to support agricultural policy promoting adaptation to climate change by linking climate scenarios, soil- and water dynamics, crops production, and economics through an integrated modelling approach[1].

The bioeconomic framework brings together four interlinked elements: long-term climate projections, crop productivity simulations, soil hydraulic modelling, and economic analysis of water competition. Climate and $CO_2$ levels feed into AquaCrop[2], which has been carefully calibrated for Finnish conditions to capture crop growth and soil moisture dynamics down to 12 soil layers. A novel approach includes new crops and intercropping systems, enabling assessment of productivity, water-use efficiency, and resilience. Model outputs are tested against in-situ soil sensor measurements to ensure grounding in real-world conditions. The novel economic component examines how water allocation options affect both agriculture and biodiversity protection in inland and coastal waters[3].

We aim to identify key temperature and precipitation thresholds affecting crop yields, soil moisture and irrigation demand. This will help to identify cost-efficient adaptive strategies for rainwater harvesting, smart irrigation systems and crop diversification. By accounting for shadow water costs, we will make transparent the trade-offs between farming needs and protecting biodiversity. These findings will feed into practical decision-support tools and shape the next stages of the project, including field trials, adaptive management and policy development.

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# Will supplemental fertigation benefit potato productions with a changing climate in Atlantic Canda?

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**ABSTRACT**

Potato is the most important cash crop in Atlantic Canada (AC). Potato is very sensitive to water supply but seasonal precipitation in AC usually meets the need for potato growth so that commercial potato cropping is mostly rain-fed in this region. However, with climate change, extreme climate events, including extended period of drought, occurred more frequently in recent years. Introducing irrigation to supplement rainfall can be a viable solution to combat drought. On the other hand, on commercial potato fields in AC, fertilizer is normally applied only once at planting thus significant nutrient loss to the environment through leaching and greenhouse gas (GHG) emissions are observed . Supplemental irrigation provides an opportunity to add fertilizer with the irrigation water (i.e., fertigation) and the application rate can be adjusted according to plant growth. Fertigation can not only increase the efficiency of N fertilizer but also reduce N loss. To test these hypothesized effects of supplemental fertigation, a field study was carried out at McCain Food Farm of the Future in Florenceville, New Brunswick. Three fields were used. Potato was cropped in a three year rotation in these fields and each year, only one field was cropped with potato. Experiments were conducted on the potato field only with three treatments: 1) full fertigation (FF), for which fertigation was applied for the entire growing season. 2) critical period fertigation (CPF), for which fertigation was only applied during the vegetative growth and tuber bulking stages; and 3) no irrigation (NI), as the control. For FF and CPF, N fertilizer rate at banding was approximately 70% of the normal rate and the N added with irrigation water was lower than 30%, resulting in an overall lower N fertilization rate. Water was applied only when soil moisture was below 70% of available water capacity. Irrigation was successful in maintaining desirable soil moisture content. NI had higher emergence rate, longer flowering period, greener leaves at earlier stages, probably due to the higher N fertilization rate at the beginning. The treatments did not show effects on stem counts, plant height and leaf stomatal conductance. The two fertigation treatments showed significantly higher total tuber yield than the control and a similar trend was observed for marketable yield , albeit the difference was not statistically significant. The two fertigation treatments also reduced the occurrence of diseases such as potato early dying and black dot, however, CPF appeared to lead to a higher risk of hollow heart. These results suggested that supplemental fertigation is beneficial in increasing potato crop productivity in AC. Field experiment is ongoing to test the treatment effects on N leaching and GHG emissions.

**Key words:** commercial potato farm, irrigation, humid cold climate

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# Effects of testing non-AI autonomous precision deficit irrigation scheduling onto potato and raspberry crops in Poland.

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**ABSTRACT**

The direct measurement of soil moisture in root zone provides an unambiguous assessment of current soil moisture and the water deficit (7, 15, 22, 25).). It allows for maintaining moisture strictly within the optimal range for a specific crop species and variety (7).

In modern irrigation support systems, sensors are permanently installed in the root system, measurements are taken hourly, and values are accessed via smartphones, which immediately calculate the optimal dose (7, 8).

It must be noted that tools providing only soil moisture percentage are practically useless unless the soil type is known, as each soil type has a different water holding capacity characteristic (11). For instance, 12% moisture might signify optimal saturation for light loamy sand, but the same value would indicate permanent wilting for clay soil (11).

Case Study: The ENORASIS Decision Support System

Precision irrigation utilizing Agriculture 4.0 technologies is exemplified by the ENORASIS system. Developed between 2012 and 2014 by a team of scientists (including IUNG-PIB) and European IT companies, ENORASIS is an innovative decision support system for agricultural irrigation (12). The project was funded by the European Commission under the 7th Framework Programme (Eco-innovation) (12).

The ICT system (22) determines irrigation needs based on mathematical models using current meteorological conditions, satellite imagery, short-term weather forecasts, and, critically, direct soil moisture measurements taken under the crop (13). Information regarding the required timing and water dose is transmitted to the farmer via SMS (cellular network), the ENORASIS website, and a mobile application (13).

The system was tested at five pilot sites: Poland (2), Serbia, Turkey, and Cyprus (15). These sites were equipped with the wireless sensor network, an automatic meteorological station, and specialized numerical weather forecast services (15). System control was managed via a web browser application and an Android mobile app (16).

Pilot results demonstrated significant effectiveness:

• In Grabów in 2014, ENORASIS-guided irrigation led to a yield increase of 61% for corn and 67% for potatoes compared to non-irrigated plots (16). This was achieved with low operational costs and significant water savings, reaching 42% (16).

• On a raspberry plantation located on shallow sandy soils, direct measurement resulted in a 10-fold reduction in water consumption (18) with no negative impact on yield (18). The owner reported slightly better qualitative parameters for the fruit and healthier plants (18).

# Climate-change-induced Increase in Rain Erosivity in Germany

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**ABSTRACT**

Rising air temperatures are shifting precipitation regimes by reducing snowfall in favor of rainfall, increasing atmospheric moisture capacity, and promoting a transition from advective to more convective rainfall. These changes should also modify rain erosivity.

Analyses of rain-gauge measurements and high-resolution radar rainfall data indicate that rain erosivity has doubled between the 1960s and 2025 in Germany. The trend has intensified markedly since the early 1990s, closely tracking the acceleration of global temperature rise. Notably, this substantial increase in erosivity has occurred without corresponding changes in monthly precipitation totals, raising questions about the suitability of the commonly used Modified Fournier Index as a proxy for estimating rain erosivity from climate projections.

The intra-annual distribution of erosivity has also shifted, with disproportionately strong increases during the cold season. As a result, the susceptibility of crops to erosion has changed. In particular, crops providing limited winter ground cover, such as winter wheat, now face substantially higher erosion susceptibility. Considering both the rise in rain erosivity and the heightened susceptibility to erosion, soil erosion in winter wheat has increased approximately fourfold over the past few decades due to climate change.

# Mapping Gully Erosion Across the European Union

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**ABSTRACT**

Gully erosion represents one of the most severe forms of land degradation in Europe, yet its large-scale distribution and drivers remain poorly documented. The 2022 LUCAS survey provides the most comprehensive EU-wide assessment to date, combining in situ and on-screen observations across 399,591 locations to map visible gully erosion features. The resulting GE-LUCAS v1.1 (Borrelli et al., 2025a) inventory identifies 3,116 sites (~0.8% of surveyed points) affected by gully erosion, with a pronounced concentration in Mediterranean regions such as Spain and Italy . Land-cover analysis shows that olive orchards alone account for ~25% of all mapped gully observations, highlighting their disproportionate exposure to severe soil degradation.

Insights from recent assessments of Mediterranean olive systems reinforce this pattern (Borrelli et al., 2025b). Intensive ground-cover removal, cultivation on increasingly steep terrain, and climate-driven droughts and high-intensity rainfall have created conditions where soil loss in olive groves routinely exceeds 29–47 t $ha^{-1}$ $yr^{-1}$, and can surpass 455 t $ha^{-1}$ $yr^{-1}$ in gully-affected areas. Spatial analyses from Andalusia further estimate 300,000–350,000 gullies in olive landscapes, far exceeding earlier approximations. These findings show that gully erosion in olives is not an isolated phenomenon but part of broader, interconnected degradation pathways involving water and wind erosion, tillage, nutrient depletion, and declining soil organic carbon.

The GE-LUCAS v1.1 dataset thus provides critical evidence that Mediterranean olive systems are emerging as early warning indicators of accelerating land degradation in Europe. Together, these results underscore the urgent need for targeted, soil-conserving management and policy interventions capable of building resilience in erosion-prone agroecosystems.

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# Can soil magnetism affect the soil response to the magnetized water?

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## ABSTRACT

Climate change induced soil and water salinization, necessitating sustainable remedies. Magnetized water (MW) technology enhances irrigation efficiency and alleviates salinity effects on soil productivity. However, several soil variables may constrain the efficacy of MW technology for irrigation. The impact of the soil magnetism (SM) on soil response to MW remains insufficiently investigated, highlighting a knowledge gap. Here we present a mineralogical, magnetic, and chemical characterization for 5 distinct Egyptian saline and non-saline soils; clayey, calcareous, and sandy soils. Furthermore, we selected 3 samples for an experimental study to evaluate their response to MW considering changes in their physico-chemical characteristics. The assessed magnetic properties: mass specific susceptibility ($\chi_{lf}$), frequency-dependent susceptibility ($\chi_{fd}$%), normal remanent magnetization (NRM), and S-ratio showed a great reliance on the mineralogical and chemical composition. The soils rich in Al, Fe, Mn, and Ti showed the highest $\chi_{lf}$ and NRM values in the range 27.6 - 8.86×$10^{-7}$$m^3$/kg and 6.83-18.6×$10^{-7}$A/$m^2$.kg for $\chi_{lf}$ and NRM; respectively) while minimum values are in soils rich in Si and Ca that were 0.37×$10^{-7}$$m^3$/kg and 0.97×$10^{-7}$A/$m^2$.kg for $\chi_{lf}$ and NRM; respectively. Calcareous and saline soils underwent MW treatment where their response was assessed via the change in physico-chemical characters; hydraulic conductivity (HC), aggregate-size distribution, pH, electric conductivity (EC), zeta potential (ζ), $CaCO_3$ (%), OM (%), soluble anions and cations, and magnetic properties. The aggregate-size distribution showed an increase in fine fraction (<90μm) in the calcareous sample while an increase in the coarse fraction (1-2 mm) by 38.2 and 35.7% took place in saline samples. Hence, MW increased the HC in saline soils by 31.4% (loamy sand) and 77.1% (sandy loam) rather than calcareous soil where HC is reduced by 25.1% compared to the non-magnetized water (NMW). Both MW and NMW significantly decreased the EC where soluble cations and anions ($Na^+$, $K^+$, $Cl^-$, and $Ca^{+2}$) were mostly washed. However, the decrease by MW is less than NMW by 12% and 26.8% in the calcareous soil and loamy sand soil; respectively and more than NMW by 31.12% in the sandy loam sample. The MW has slightly decreased the $\chi_{lf}$ and NRM for all samples with no significant changes in S-ratios, while the $\chi_{fd}$% significantly dropped by 47.36% and 88.76% in the saline samples, indicating a great reduction in the super-paramagnetic (SP) particles content. Overall, MW affects the soil chemically, physically, electrically, and magnetically. The interactive effect of MW and SM, depending on the aforementioned factors, may decide its efficiency for MW technology application in the agricultural field. However, the overall effect of the MW on soil cannot be predicted, and each soil type may be a special case of complex interactive factors differing with soil conditions and irrigation water source.

# Theory and Demonstration of Smart Water and Soil Management Technologies for Black Soil Cropland

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**ABSTRACT**

Extreme climate change has heightened the uncertainty of hydrological processes in the Black Soil Region, northeast China, leading to concurrent risks of drought and waterlogging alongside runoff-induced erosion, which threatens soil conservation and crop production. Drawing upon the differentiated soil, climate, and agricultural production factors in Northeast China, this study establishes a smart water and soil management strategy for Black Soil cropland to adapt to climate change. By utilizing an integrated space-air-ground monitoring system to assess soil physicochemical properties and the type and severity of degradation, we constructed a precision water control system that integrates surface and subsurface measures—specifically contour tillage, cultivable ridges, subsurface drainage, and vertical shafts. The system is coupled with soil optimization techniques, such as variable fertilization to achieve comprehensive regulation of water and soil resources. Furthermore, supported by an intelligent management platform and mobile APP, the system enables the intelligent configuration of the full operational workflow, encompassing "monitoring, diagnosis, decision-making, and execution." The implementation of this integrated system facilitates precise water regulation and soil optimization management, significantly enhancing the capacity for soil erosion control and water use efficiency under extreme climate conditions, thereby providing tailored solutions for the sustainable utilization of soil resources.

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# Sustainability challenges of vegetation restoration on the Loess Plateau

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**ABSTRACT**

As one of the most serious soil erosion regions in the world, the Loess Plateau has received extensive international attention for the effectiveness of soil and water conservation stages and the ecological adaptability of vegetation configuration patterns. In recent years, large-scale afforestation has significantly improved the vegetation cover of the Loess Plateau, and the erosion condition has been mitigated at a stage, and the ecosystem function has been initially restored. However, the early vegetation restoration process exists species configuration homogenization, spatial layout homogenization and other problems, despite the increase in vegetation cover, but the stability of the vegetation structure is insufficient, transpiration caused by the increase in the soil moisture deficit is also increasingly apparent, part of the regional vegetation restoration has exceeded the ecological carrying threshold, a serious constraint on the long-term stability of soil and water conservation benefits. In response to the lack of vegetation sustainability exposed by the current ecological restoration mode of "promoting the whole region", we propose an adaptive zoning management strategy based on topography, rainfall pattern and climatic gradient, delineate differentiated vegetation restoration zones, and construct near-natural vegetation restoration standards in different habitats, in order to optimize the vegetation restoration layout and optimize the water and soil conservation management strategy for the Soil and Water Conservation Program on the Loess Plateau under the background of climate change. This provides theoretical support and practical paths for the optimization of vegetation restoration layout and the sustainable and stable performance of soil and water conservation benefits in the context of climate change on the Loess Plateau.

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# From Free-Draining to Flood-Forming: How Compaction and Slaking Generate Runoff in Sandy Soils Under Extreme Rainfall

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**ABSTRACT**

Climate change is increasing the frequency and intensity of extreme rainfall in the UK, with annual totals rising by around 30% in Southwest England over the last century and storm intensities exceeding 30 mm $hr^{-1}$. Light sandy soils, such as the Bromsgrove series over Triassic sandstone, are naturally free draining and typically saturate at only 40–50%. As a result, the UK Centre for Ecology and Hydrology Flood Estimation Handbook classifies them as low risk for overland flow. However, recent flood events linked to cultivated sandy soils have revealed a growing vulnerability, with sediment-laden runoff damaging homes, infrastructure, and drainage systems.

Intensive land management can transform these normally permeable soils into runoff-prone surfaces. Compaction from machinery or livestock reduces infiltration capacity, while extreme rainfall can trigger slaking, where rapid aggregate breakdown forms a thin sand–silt seal that further restricts infiltration. Together, these processes create conditions in which even free-draining sandy soils generate overland flow.

To investigate these mechanisms, field trials (July–October 2025) compared infiltration and sediment runoff under soil water-deficit conditions. Replicated plots of cultivated bare soil, newly established grassland, and maize (growth stage 5-6) were subjected to simulated rainfall at 74 mm $hr^{-1}$, representing a projected late-21st-century 1-in-150-year event for Southwest England under Hadley Centre RCP 8.5 scenarios. Surface runoff ranged from 36% in compacted maize plots to zero in newly established grassland. Bulk density in wheelings reached 1.55–1.90 g $cm^{-3}$, compared with 1.22–1.30 g $cm^{-3}$ in untrafficked soils. Soil organic matter was low (3.5–4.0%), typical of long-term cultivated mineral soils. Exposed post-harvest soil produced peak sediment concentrations >20,000 mg $L^{-1}$, while grassland produced none and trafficked maize plots yielded 2,000–8,000 mg $L^{-1}$.

Laboratory rainfall simulations supported these findings: aggregate stability was initially 60–80% after 40 minutes at 74 mm $hr^{-1}$ but fell below 10% on second exposure, demonstrating that aggregate breakdown is cumulative. Repeated rainfall progressively weakens aggregate structure, increasing susceptibility to sealing and runoff.

Overall, the results show that sandy soils long regarded as free draining can become flood-forming systems when affected by compaction and surface slaking. In contrast, grassland cover and good soil condition maintained infiltration even under extreme rainfall, highlighting the importance of soil management in mitigating climate-driven runoff risks.

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# Cross scale assessment of agricultural conservation measures for future erosion, soil carbon and crop yield in the Yangtze River Basin

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## ABSTRACT

Soil erosion, exacerbated by climate change, threatens agricultural productivity and carbon sequestration in the Yangtze River Basin (China), highlighting the need for effective conservation strategies. However, the combined impact of climate change and land use change on soil erosion remains poorly understood, and the effectiveness of agricultural conservation measures at the basin scale is largely unknown. Here, we develop a cross-scale framework that integrates process-based modelling (using the PESERA model), meta-analysis, and machine learning to project future trajectories (2020-2060) of soil erosion, aboveground biomass (AGB), soil organic carbon (SOC), and crop yields under multiple climate and land-use scenarios, and to quantify the implementation effects of agricultural conservation practices across the Yangtze River Basin. Our results show that soil erosion rates showed an increasing trend under all four SSP scenarios, but with varying magnitudes of increase. Specifically, the increases in soil erosion were particularly pronounced under SSP2-4.5 and SSP5-8.5 scenarios, reaching 54.0% and 50.4% above the 2020 baseline level by 2060, respectively. In contrast, the increases were relatively moderate under the sustainable development pathway SSP1-2.6 and the regional rivalry pathway SSP3-7.0 scenarios, at 8.8% and 10.3%, respectively. AGB increased significantly under the SSP1-2.6, SSP2-4.5, and SSP3-7.0 scenarios (with increases ranging between 19.5% and 20.7%), but showed a smaller increase (11.1%) under the SSP5-8.5 scenario. The trend in SOC was closely related to emission levels: it increased (by approximately 7.6%) under low-emission scenarios (SSP1-2.6 and SSP2-4.5), but decreased (by 4.0% and 6.9%, respectively) under high-emission scenarios (SSP3-7.0 and SSP5-8.5). Crop calorie output increased slightly (by 3.8%) under SSP2-4.5, remained essentially stable (a slight decrease of 0.1%) under SSP1-2.6, but decreased by 12.4% and 38.5% under SSP5-8.5 and SSP3-7.0, respectively. An optimized combination of soil and water conservation measures (SWCM) can substantially reduce mean soil erosion on croplands by 75.3%, while increasing SOC by 20.7% and crop yield by 15.4%, relative to a no-conservation scenario (SSP5-8.5). Bridging field evidence with basin-scale projections, our integrated analysis demonstrates the value of targeted SWCM implementation in enhancing soil conservation, carbon sequestration, and food security, providing timely insights for climate-resilient land management in the Yangtze River Basin and beyond.

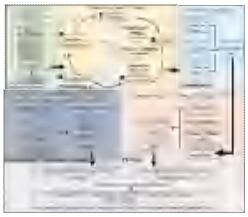


**Fig. 1** A schematic workflow for the spatiotemporal distribution assessment of soil erosion, soil organic carbon and aboveground biomass using the Metronamica and Pan-European Soil Erosion Risk Assessment (PESERA) models under SSP-RCP scenarios.

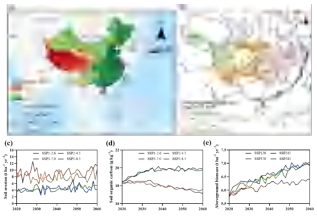


**Fig. 2** Elevation for China, with the Yangtze River Basin highlighted by the red frame (a). Climate zones as used for Yangtze River Basin to vary crop calendars by agroclimatic zone(b). Interannual variations of soil erosion (c), soil organic carbon (d), and aboveground biomass (e) from 2020 to 2060 under climate and land use change scenarios.

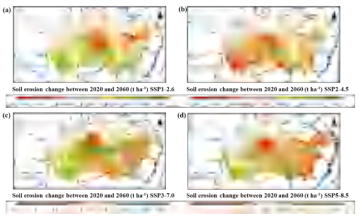


**Fig. 3** Soil erosion changes between 2020 and 2060 under different SSP-RCP scenarios, with SSP1-2.6 (a), SSP2-4.5 (b), SSP3-7.0 (c) and SSP5-8.5 (d).

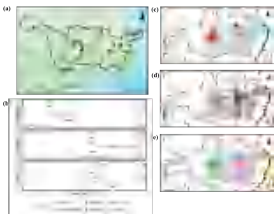


**Fig. 4** Geographical distribution of field observations used in the meta-analysis (a). The overall mean response of soil erosion, yield and soil organic carbon (SOC) to the soil and water conservation measures. "All" represents the overall effect of all soil and water conservation measures. The numbers denote the number of observations. The black dashed line denotes an average effect value of 0 (b). Predicted potential changes in relative soil erosion (c), SOC (d), and crop yield (e) resulting from soil and water conservation practices in the Yangtze River Basin, based on a random forest model.

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# Paleo-landscape features and their role for soil erosion initiation

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**ABSTRACT**

Soil erosion by water is depending on the classical factors like soil erodibility, rainfall erosivity landuse and landcover pattern as well as agricultural management practices and topographic characteristics. Having the respective combination and intensities of these factors specific soil erosion processes may develop. Thus, different soil erosion processes can be simulated if the relevant input data are available. However, the role of other influencing factors such as frost process dynamics, the influence of soil fauna, subsoil features, or the role of Paleo-landscape features is often neglected in soil erosion assessments. Particularly, the Paleo-landscape features may play a more significant role than expected, at least in specific environments characterized by different climatic conditions in the past. Our study investigates two different case studies in semi-arid areas of Southern Africa and in a cold Northern-hemisphere climate. In our study we particularly focus on gully erosion. We show that paleo-processes and related landscape characteristics still influence present day dynamics. We show for the two study cases why and where in the present-day landscape soil erosion processes may occur. The results reveal that the prediction of soil erosion susceptibilities increases significantly if Paleo-landscape features are taken into account.

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# Porous Biochar Produced from Rice Waste Inhibits Soil Loss

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## ABSTRACT

Soil and water are fundamental resources for human and other living organisms, and their degradation can entail irreparable consequences. It also plays a key role in food security, the national economy, and sustainable agriculture. Therefore, efficient and effective protection of soil and water, in light of population growth and unsustainable exploitation of natural resources, is of particular importance. The presence of waste arising from various activities has created short- and long-term adverse environmental impacts. Today, environmental protection and waste recycling are among the most critical issues in human societies. Given the finite nature of resources, researchers are seeking ways to optimize the use of unusable waste. Among various additives and modifiers, biochar can play a significant role in waste management. In this regard, this research was planned to manage rice waste and convert it into morphogenetic porous biochar for use at a 5% weight to control and reduce surface runoff and its components. For this purpose, rain simulation experiments on loess soil were conducted on the scale of small experimental plots with dimensions of 0.5×0.5 m with a slope of about 15% under rainfall with an intensity of about 70 mm $h^{-1}$ lasting for 30 min with three repetitions in the Rain and Erosion Simulation Laboratory of Tarbiat Modares University, Iran. The results of the study showed that the treatment combined with porous rice straw biochar significantly ($p<0.001$) increased the time to runoff, runoff volume, and runoff coefficient by 87.65%, 70.72%, and 70.33%, respectively, compared with the control treatment. According to the results, morphogenetic porous biochar can be used as an effective and sustainable solution for managing erosion-sensitive soils and for improving conservation agriculture, soil and water conservation, and waste management. The outcomes of this study provide a solid scientific basis for developing actionable guidelines to safeguard soil and water resources and improve the performance of agricultural products.

**Acknowledgments**

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# Slope Aspect Affects Soil Quality and Its Response to Soil Erosion on Temperate Gentle Sloping Farmlands

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**ABSTRACT**

Slope aspect is a significant terrain attribute influencing soil physical and chemical processes. Yet its impact on soil quality and erosion has rarely been studied on gently sloping farmlands. The objective was to evaluate the effects of slope aspect on soil quality and its response to soil erosion in the black soil region of northeast China, a temperate environment featuring gently sloping farmlands. Over a nearly north-south symmetric sloping farmland spanning ~ 3500 m, fifteen soil physical and chemical properties were investigated at every 40 m, and an integrated soil quality index (SQI) was calculated combining principal component analysis and scoring functions. The mean annual erosion rate (ER) was estimated using the cesium-137 tracing technique. Compared to the south-facing slope, the north-facing slope possessed significantly lower pH and higher saturated hydraulic conductivity, sand content, and almost all the essential nutrient contents, therefore overall better soil quality ($p < 0.05$). No statistical difference was spotted in ER between the two slopes ($p > 0.05$); however, erosion was found to deteriorate soil quality via distinct pathways. On the north facing slope, erosion affected SQI predominantly through its negative impact on soil organic carbon content and wet-aggregate stability, and conservation tillage practices were suggested. However, on the south-facing slope, the detrimental influence was primarily driven through the depletion of soil nutrient contents, particularly available phosphorus and total nitrogen, and contour tillage and hedgerows were strongly recommended. These findings hold important practical implications for agricultural management in temperate environments.

**Acknowledgments**

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# Biochar application ameliorates soil and water loss on the soil-mantled karst slopes: mechanisms and benefits

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**ABSTRACT**

Karst regions face severe challenges associated with soil erosion and land degradation. Their unique geological structure, characterized by shallow soil layers covering highly permeable bedrock, leads to significant surface soil loss and substantial "hidden" subsurface soil and water leakage through fissures and conduits. This phenomenon not only accelerates rocky desertification but also causes severe nutrient depletion and poses considerable agricultural and ecological risks. Biochar, a porous carbonaceous material with high adsorption capacity and chemical stability, has emerged as a promising soil amendment. However, its synergistic mechanisms in controlling the dual-surface and subsurface soil and water loss processes on karst slopes remained inadequately understood. This study employed an integrated approach combining field in-situ monitoring, controlled micro-plot experiments, and laboratory analyses. On soil-mantled karst slopes, experimental plots were established with different biochar application rates (e.g., 0 wt%, 1.36 wt%, and 2.72 wt%). We comprehensively monitored surface and subsurface runoff volumes, soil loss quantities, and changes in nutrient concentrations (e.g., nitrogen, phosphorus). Concurrently, we analyzed responses in soil physical structure (e.g., aggregate stability, porosity, water infiltration and retention characteristics), chemical properties (e.g., organic matter, pH, nutrient forms), and microbial community structure (via high-throughput sequencing). The findings reveal that biochar significantly regulates hydrological processes by improving soil physical structure. It enhances soil aggregate stability and pore connectivity, thereby delaying rapid water infiltration, reducing the risk of strong subsurface preferential flow, and increasing soil volumetric water content by 15-25%, which markedly improves soil drought resistance. Consequently, biochar effectively reduces total surface runoff (by 25-35%) and soil loss (by over 35%), while simultaneously decreasing subsurface runoff (by 10-20%) and its associated sediment transport. Regarding nutrient retention, biochar directly immobilizes nutrients like nitrogen and phosphorus in the soil via its adsorption capacity, leading to a reduction in nitrate-nitrogen and soluble phosphorus losses via surface and subsurface pathways by 20-30% and 15-25%, respectively, thereby significantly mitigating non-point source pollution risks. Furthermore, biochar indirectly enhances soil fertility by modulating the soil bacterial community; it notably enriches beneficial phyla such as Actinobacteria and Proteobacteria, which promotes the decomposition and sequestration of soil organic matter and drives carbon and nitrogen cycling, ultimately improving fundamental soil fertility. In conclusion, biochar plays multiple roles in soil and water conservation and fertility enhancement in karst regions. Its mechanism of action constitutes a multi-pathway synergistic process, initiating from the improvement of soil physical structure, extending to the regulation of hydrological processes, and culminating in the optimization of nutrient cycling and the enhancement of microbial ecosystem functions. This research provides a solid theoretical foundation and an effective technical pathway for ecological restoration and sustainable agricultural development in these vulnerable areas.

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# A systematic identification of multi-scale relationship between sediment load and environmental factors in the Ten Tributaries region of the Yellow River Basin

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**ABSTRACT**

The sediment load is an important indicator that reflects soil erosion in a watershed. The temporal variation of sediment load usually has scale dependence and is influenced by different environmental factors. However, due to the potential overlap of various factors at different scales, the complex multi-scale relationship between sediment load and its potential influencing factors remains unclear. The aim of this study was to analyze the multiscale correlations among runoff, precipitation, evaporation, and NDVI on monthly sediment load in the Ten Tributaries region of the Yellow River Basin from 2007-2021. The results showed that the sediment load, runoff, and precipitation showed strong variability, while evaporation and NDVI showed moderate variability in three watersheds (Maobula, Hantaichuan and Xiliugou) of the Ten Tributaries region. The original time series of the sediment load, runoff, precipitation, evaporation and NDVI were all decomposed into six intrinsic mode functions (IMFs) and a residue based on multivariate empirical mode decomposition (MEMD). The cumulative variance contribution rates of IMF1, IMF2, and IMF3 of variables all exceeded 90% within the three watersheds. The TDIC shows the associations between sediment load and the controlling factors changed significantly with the scale, which have multi-scale dynamic properties. Runoff was the key factor affecting sediment load in Maobula and Xiliugou watershed. In Hantaichuan watershed, runoff dominated sediment load dynamics from IMF1 to IMF5, whereas PET governed the sediment transport process at IMF6. Three machine learning models, multilayer perceptron (MLP), convolutional neural networks (CNN) and particle swarm optimization-support vector regression (PSO-SVR) were applied to forecast sediment load in different basins. Integrating MEMD with ML significantly enhanced sediment load prediction accuracy.

# SOIL MANAGEMENT AND CONSERVATION FOR AGRICULTURAL SUSTAINABILITY IN MALI VILLAGES

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## ABSTRACT

The agroecosystems of Mali (West Africa) are experiencing degradation of Plinthic soils driven by surface crusting, low permeability (2.5–12.7 mm $h^{-1}$), low soil organic matter (7.8–22.8 g $kg^{-1}$), and consequent severe sheet erosion. Beyond inadequate management and limited use of Soil and Water Conservation Practices (SWCP), decision-relevant information for sustainable soil conservation and food security remains scarce. This study evaluated the potential to implement SWCP through a Technical Demonstration Unit (TDU) aimed at mitigating soil degradation and sustaining agricultural productivity in the villages of Siani and Bandiagara II. Within the TDU, three SWCP were established on the level contour: narrow-based terraces (NBT), stone cordons (SCN), and vegetation cordons of *Pennisetum purpureum* (VCN). These practices were tested with the following intercrops for corn (*Zea mays*) and cotton (*Gossypium hirsutum*): *Brachiaria ruziziensis* (IZB, IGB), *Vigna unguiculata* (IZV, IGV), *Arachis hypogaea* (IZA, IGA), corn + *Stizolobium aterrimum* (IZS), cotton + *Stylosanthes guyanensis* (IGS), and controls without SWCP (ZWC, GWC). In 2024, IGS was replaced by cotton + *Crotalaria ochroleuca* (IGC). In 2022, IZS produced 13.50 t $ha^{-1}$ of green biomass and the highest corn grain yield (4.40 t $ha^{-1}$). For cotton, green biomass reached 4.50 t $ha^{-1}$, with the highest lint + seed yield of 1.27 t $ha^{-1}$ under level planting. In 2023, for corn, the SCN with IZS produced the highest green biomass (19.92 t $ha^{-1}$) and grain yield (4.24 t $ha^{-1}$). For cotton, SCN with IGA produced the highest green biomass (13.25 t $ha^{-1}$) and lint + seed yield (2.50 t $ha^{-1}$). In 2024, NBT with IZV achieved the highest corn green biomass (29.83 t $ha^{-1}$) and grain yield (6.83 t $ha^{-1}$). For cotton, the highest lint + seed yield was 2.43 t $ha^{-1}$, while the highest green biomass (7.24 t $ha^{-1}$) occurred under VCN with IGA. Overall, adoption of SWCP increased biomass inputs and maintained soil cover, resulting in higher corn and cotton yields that consistently exceeded national averages in Mali.

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# Decoding impacts of slope length on sheet erosion based on calculus method

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**ABSTRACT**

Slope length is a critical topographic factor influencing sheet erosion, yet conventional whole-slope averaging fails to reveal dynamic variations of erosion rate across continuous slope length. This study, conducted indoor rainfall simulations with 5 rainfall intensities (0.800, 1.040, 1.700, 2.475, and 2.835 mm $min^{-1}$), 5 slope gradients (0.1763, 0.2679, 0.3640, 0.4663, and 0.5774), and 5 slope lengths (0.4, 0.8, 1.2, 1.6, and 2.0 m), defined slope position runoff rate ($R_i$) and slope position erosion rate ($D_i$) as continuous spatial functions of slope length via calculus, and systematically analyzed their variation characteristics and driving mechanism. Results indicated that $R_i$ increased and then decreased along slopes in most cases, with the turning point moving from approximately 0.8 m down to 1.0 m under increasing rainfall intensity. $D_i$ with slope length showed a decrease-increase trend under steep slopes with high rainfall intensity and an increase-decrease trend under gentle slopes with low rainfall intensity, with turning points migrating downslope as rainfall intensity and slope gradient increased, as well as being susceptible to net deposition at slope bases under certain circumstances. Regression equations suggested that the effect of rainfall intensity on $R_i$ and $D_i$ diminished with slope length, while the effect of slope gradient strengthened on lower slope segments. For entire slopes, rainfall intensity played the greatest role in erosion (Pearson's r = 0.71, total effect = 0.71), followed by $R_i$ (0.68, 0.19) and sediment concentration (0.59, 0.45). Spatially resolved structural equation modeling (SEM) revealed progressive control shifts along the slope, confirming three-phase erosion dynamics: upslope rainfall-driven erosion (direct path coefficient = 0.86), mid-slope runoff-mediated transport (0.75), and downslope sediment-regulated deposition (0.65), reflecting a hydrodynamic transition from raindrop detachment to flow-driven transport and sediment deposition. This study reveals slope erosion-deposition dynamics and provides a theoretical basis for the parameterization of slope length in process-based erosion models.

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# Setting tolerable soil loss and land management targets across New South Wales, Australia

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**ABSTRACT**

Setting tolerable soil loss (TSL) targets is necessary for sustainable land use and land management practices. In this study, we developed a new approach to monitor sustainable land management using widely available remotely sensed data, such as fractional vegetation cover (FVC) data derived from satellite data (MODIS, Landsat and Sentinel) (Yang et al. 2022). The method is based on the concept of maintaining sufficient vegetation cover to meet the TSL goals which vary spatially and temporally, not being static as in most reported studies to date. We determined monthly TSL thresholds based on long-term natural erosion rates, soil and landscape capabilities, and land uses at a given location. Where vegetation cover is more than that required to meet the TSL goal at a given location and time, the site is deemed to be managed sustainably (Gray et al. 2023). Monthly FVC and rainfall erosivity time series over the period from 2001 to 2025 have been used to estimate hillslope erosion rates and compared with the TSL targets across New South Wales (NSW), Australia. These monthly indices are then combined to form yearly sustainable land management indices (SLMI) over the 26-year period (2001-2025). We applied this new method across NSW and assessed the SLMI against soil and landscape capability classes and their spatial and temporal variation across local land service regions. High-resolution satellite data and field measurements have been used to validate the estimated FVC and erosion rates at selected field sites. Findings from this study can be used to identify the locations and periods of time with hillslope erosion exceeding a desirable TSL threshold level and indicate where management actions might be required to improve the soil condition over areas of concern. This new method is also globally portable as the required input datasets are widely available.

**Acknowledgments**

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# Predicting Current and Future Erosion Risk across NSW, Australia

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**ABSTRACT**

Rainfall erosivity is one of the most dynamic factors in the soil erosion process. The increase in soil erosion caused by high rainfall erosivity, and the subsequent loss of soil nutrients, can lead to reduced food production and ecosystem services. This research predicts rainfall pattern changes, rainfall erosivity and erosion risk across New South Wales (NSW) using the NSW and Australian Regional Climate Modelling (NARCliM) projections. We predict the rainfall erosivity across NSW under current and future climate changes under low to high emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0) from the baseline (1990–2009) to the future (2025–2100) periods. We utilized the Revised Universal Soil Loss Equation (RUSLE) to estimate monthly time-series soil erosion risk. The results indicate that the annual average rainfall erosivity is approximately 12% lower under the low emission (SSP1-2.6) scenario and 6% lower under the high emission (SSP3-7.0) scenario across NSW compared to results from observations. This might be due to the projected temperature rise, and consequently the increases in vegetation cover. Despite the underestimates, the absolute bias (0.25) from the NARCliM2.0 projection is far less compared to the previous versions (0.46 for NARCliM1.0 and 0.42 for NARCliM1.5). This improvement is consistent across all seasons, indicating the refinements in the new version (2.0) and its enhanced capacity to predict soil erosion with higher accuracy. Such improvements are crucial for reliable climate modelling and can significantly impact regional decision-making in climate adaptation strategies. With the ongoing development of NARCliM2.0, we expect enhancements particularly at higher temporal resolutions (hourly or sub-hourly) to enable better capture of extreme rainfall events.

**Acknowledgments**

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# Slope Gradient Modulates Pathways of Soil Erosion-Induced Corn Yield Losses in Northeast China's Black Soil Region

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**ABSTRACT**

The Northeast Black Soil Region is a vital grain production base in China, contributing >40% of the national corn output. However, soil erosion on sloping farmlands drives progressive thinning of the mollisol layer and fertility decline, threatening both national food security and sustainable black soil utilization. Through a two-year field experiment on two representative slopes (3° vs. 5°) in this region, we investigated spatial patterns of soil erosion and corn yield, and elucidated mechanisms linking erosion to yield losses. Key results indicate: (1) Net erosion rates reached 4,482.90 and 3,864.50 t $km^{-2}$ $yr^{-1}$ for 5° and 3° slopes, respectively, classifying both as moderate erosion (significantly exceeding the tolerable loss limit of 200 t $km^{-2}$ $yr^{-1}$). The 5° slope exhibited a 16.00% higher erosion rate than the 3° slope ($p < 0.05$). (2) Soil erosion/deposition rates strongly correlated with corn yield ($R = -0.72$, $p < 0.001$), with each 1 t $ha^{-1}$ $yr^{-1}$ increase in erosion reducing yield by 0.04 t $ha^{-1}$. (3) Mollisol thickness negatively correlated with erosion rate ($p < 0.05$) but positively correlated with yield ($p < 0.05$), confirming erosion indirectly reduces yield by thinning the mollisol layer. (4) On the steeper 5° slope, higher erosion directly reduced yield while also exerting indirect effects via mollisol loss; in contrast, on the gentler 3° slope, yield enhancement was achievable by increasing soil organic matter (SOM) and reducing soil erodibility (K-factor). Summary, Erosion control measures (e.g., mulching) should be prioritized on steep slopes (≥5°) to maintain mollisol thickness, while gentle slopes (≤3°) benefit more from organic amendments that boost SOM and reduce erodibility, thereby securing corn productivity.

Keywords: Slope gradient; Soil erosion; Corn yield; Mollisol

# Effects of the size of biodegradable superabsorbent polymers on interrill erosion

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**ABSTRACT**

Superabsorbent polymers (SAPs) have been applied in agricultural fields to improve productivity. SAPs can also influence soil erodibility through various mechanisms, such as suppression of rainfall-induced surface runoff due to water absorption, swelling–shrinkage–induced disruption of soil structure, and reformation of soil aggregates through incorporation of soil particles into the gel matrix. However, quantitative data applicable to erosion prediction models such as USLE and WEPP remain limited. Furthermore, conventional SAPs may potentially act as new sources of microplastic pollution. The biodegradable SAPs has recently been used. In actual farmland, granular biodegradable SAPs are spread by machine, so it is necessary to evaluate the effect of changes in size due to decomposition on erosion. In this study, laboratory experiments were conducted to examine the effects of biodegradable SAPs and their sizes on interrill erosion caused by raindrop impact under rainfall conditions.

The soil of light clay was collected from the upland field in Hokkaido University, Japan. A commercially available biodegradable SAPs (EFP, EF Polymer Co., Ltd.) were separated into two size fractions: 1-5 mm and 0.053–0.5 mm. Each SAP was mixed into the soil at mass ratios of approximately 0.002% and 0.02%, respectively. 0.02% is an excessive concentration that is 10 times higher than that applied to farmland. Together with the untreated control, five soil treatments were prepared. The prepared soils were packed into erosion test boxes. One day before the experiment, the soil was moistened to a volumetric water content of approximately 36% to enhance its susceptibility to erosion. The soil boxes were placed on an inclined platform, and simulated rainfall was applied at intensities of 20–40 mm $h^{-1}$ for predetermined durations. Runoff samples were collected at 5-minute intervals to measure the amount of runoff water and eroded sediment. After rainfall, soil samples were collected from soil box to measure soil physical properties.

In this study, there was no clear difference in the start of runoff from soil regardless of treatments. This was supported with the lack of significant differences in the saturated hydraulic conductivity of the soil under each treatment. Furthermore, there was no significant difference in interrill erodibility factor calculated form runoff water and eroded sediments. The interrill erodibility factor is related to the stability of soil aggregates, and there was also no difference in the mean weight diameter of soil aggregates for each treatment. In this study, it was considered that the difference of SAP size and the excessive application may not have a significant effect on soil interrill erodibility. Future studies should examine the potential aggregate stabilization caused by long-term decomposition of biodegradable materials and its impact on erosion.

**Acknowledgments**

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# A study on soil erodibility and the applicability of estimation methods in Robinia pseudoacacia L. mixed forests on the Loess Plateau, China

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## ABSTRACT

Soil erodibility serves as a crucial indicator for assessing soil sensitivity to erosion and is a vital parameter in soil erosion prediction models. The mixed transformation of *Robinia pseudoacacia L.* forests leads to variations in the root morphology of understory vegetation, which subsequently affects soil erodibility. This study focused on five typical mixed forests: *Robinia pseudoacacia L.* with *Prunus sibirica L.*, *Prunus davidiana Franch.*, *Hippophae rhamnoides L.*, *Amorpha fruticosa L.*, and *Pinus tabuliformis Carrière.* The study analyzed how soil erodibility changed after mixing the *Robinia pseudoacacia L.* forests, as well as the response mechanisms to root morphology and aggregate stability. Simultaneously, the study has explored an estimation method for soil erodibility in woodland, utilizing parameters of aggregate particle size distribution. The results showed that mixed planting of *Robinia pseudoacacia L.* with *Prunus sibirica L.*, *Prunus davidiana Franch.*, and *Pinus tabuliformis Carrière* reduced soil erodibility by 1.33%, 3.72%, and 3.79%, respectively. In contrast, mixed planting with *Hippophae rhamnoides L.* and *Amorpha fruticosa L.* increased soil erodibility by 6.09% and 3.63%. The soil erodibility of ephemeral gullies increased by an average of 7.18% (5.43%-8.37%) compared to slopes. Changes in root traits and aggregate stability resulting from the mixed planting of *Robinia pseudoacacia L.* accounted for 93.5% of the soil erodibility. Aggregate stability was the primary factor influencing soil erodibility, with a standardized path coefficient of -0.865 ($p$<0.001). Roots primarily reduced soil erodibility indirectly by enhancing aggregate stability, with a standardized path coefficient of 0.553 ($p$<0.01) for the effect of roots on aggregate stability. In the TORRI and EPIC models, estimating soil erodibility based on soil aggregates was feasible on the Loess Plateau ($R^2$=0.26, $p$<0.05; $R^2$=0.52, $p$<0.001), aligning with the hypothesis of this study. The research findings clarify suitable tree species for mixed afforestation and provide scientific References for optimizing planted forest transformation.

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# Early detection of runoff erosion as gully prevention strategy in sandy tropical soils, Kananga, Democratic Republic of Congo (DRC)

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**ABSTRACT**

Early detection and reduction of runoff erosion aim to prevent gully erosion in sandy soils in Africa. Gully erosion is considered a menace in African cities because of its recurrent spatial distribution on densely populated areas, were young and vulnerable population converge, exacerbated by social, health and political factors. This phenomenon has been documented only for the past decade. Fanjana *et al* (2025) report 18 African countries where gully erosion has been studied. The Democratic Republic of Congo (DRC), the Central African Republic (CAR) and the Republic of Congo are some of the most affected. Gully erosion has also been documented in Brazil, the city of Buritucupu being the most affected (Ferreira and Ferreira, 2021), with similar origin, size and affectation as in Africa. Mawe *et al.* (2025) identified 2922 urban gullies across 26 cities in the DRC using satellite imagery. However, no field data or site testing was conducted in either case. In Kananga DRC, we have documented gully erosion through satellite imagery and demonstrated exponential growth since 2010, UAV-lidar, photogrammetry and cloud point techniques have been used to map urban growth, vegetation cover and soil management practices in between seasons.

Spectral firms are proposed to recognize the ground features of runoff erosion associated with gully erosion development, and the specific conservation agricultural practices as a NBS prevention strategy. We propose UAV-lidar as the ideal mapping and monitoring tool for the spectral firm assessment, since it can provide a rapid, consistent, repeatable, non-destructive, and objective sampling method to assess potential erodibility due to plant-soil properties based on land-crop reflectance.

Preliminary findings point to linear infrastructure, uncontrolled urban growth and unfit agricultural practices as the main causes of soil erosion in Kananga. Thus, drainage masterplans, urban planning, landscape management and conservative soil use are some of the erosion strategies that could serve for hazard reduction.

This communication is about assessing soil degradation and stability risks and evaluating the effectiveness of NBS to reduce soil erodibility through the combination conservation agriculture, and engineering risk management in urban and peri-urban environments, also aiming to prevent runoff erosion to avert gully development in climate change challenged areas.

**Key words:** Runoff, gully erosion, NBS, sandy soils

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# From regional to global tillage erosion mapping: challenges, solutions and a demonstration in Canada

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**ABSTRACT**

Soil erosion contributes to declining soil health in agricultural land. Tillage erosion has been recognized as a major form of soil erosion, and its contribution often exceeds that of water and wind erosion in cultivated fields. However, tillage erosion has mostly been studied at the field scale, and little effort has been made to map it at regional or global scales. The major challenges for such large-scale mapping include: (1) existing tillage erosion models are all field-scale models and are not suitable for regional or global applications; (2) a lack of erosivity data for diverse cropping systems; and (3) insufficient field-scale topographic data.

To address these challenges, we developed a simplified modeling framework, the Tillage Erosion Risk Indicator (TillERI), for estimating tillage erosion, and demonstrated its application for mapping tillage erosion risk in Canada. The TillERI model operates at the spatial level of Soil Landscape of Canada (SLC) polygons, the mapping units of the national soil database. Tillage erosion was calculated as the product of tillage erosivity and landscape erodibility. Tillage erosivity was determined for major cropping systems (defined by crop type and tillage type) based on their typical tillage sequences. Cropping data were extracted from the Census of Agriculture (a national agricultural survey conducted every five years). Tillage erodibility was calculated using topographic data (slope length and gradient) generated for major landforms in the national soil database. The resulting tillage erosion rates were aggregated at the SLC polygon, provincial, and national levels.

Our results showed that the risk of tillage erosion on Canadian cropland has steadily declined since the 1980s, largely due to the adoption of conservation tillage, particularly no-till systems. The shift from annual crops to perennial crops also contributed to this declining trend. Among the provinces, tillage erosion risk was highest in the prairie provinces, where landscapes are dominated by hummocky and undulating landforms. However, areas with unsustainable levels of tillage erosion were present in every province. The TillERI results can help decision-makers better identify hotspots of tillage erosion and design policies to mitigate its impacts. The methodology can be adapted and applied to other countries or at the global scale.

**Keywords:** Soil erosion, Risk indicator, Tillage erosivity, Landscape erodibility

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# Development Characteristics and Influencing Factors of Gullies in Typical Region on the Qinghai-Xizang Plateau from 1970 to 2025

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**ABSTRACT**

To clarify the long-term development characteristics of gullies and explore the significant influencing factors of gully erosion for providing a theoretical References for soil and water conservation on the Qinghai-Xizang Plateau under the background of climate change, this study extracted the morphological parameters and development rates of stable gullies, developing gullies, and newly formed gullies on the alluvial-proluvial fans at the southeastern foothill of the western Nyainqêntanglha Mountains, based on high-resolution remote sensing images of 1970 and 2025. Spearman correlation analysis was employed to identify the significant influencing factors of the development rates of developing gullies and the morphological characteristics of newly formed gullies. In 2025, the average lengths of stable, developing, and newly formed gullies were 265.42 m, 401.61 m, and 123.12 m, respectively; and the average areas were 12 350.93 $m^2$, 7 517.52 $m^2$, and 1 055.36 $m^2$, respectively. The average linear development rate of developing gullies was 2.35 m/a, and the average areal development rate was 21.24 $m^2$/a. The linear development rate was significantly positively correlated with catchment area and near-surface air temperature ($p<0.05$). The areal development rate was significantly or highly significantly positively correlated with catchment area, elevation, and near-surface air temperature ($p<0.01$). The length of newly formed gullies was significantly positively correlated with catchment area and near-surface air temperature ($p<0.01$), and significantly negatively correlated with the maximum freezing depth of seasonal frozen ground ($p<0.05$). The area of newly formed gullies was highly significantly positively correlated with catchment area, annual precipitation, and rainy season precipitation ($p<0.01$), but highly significantly negatively correlated with the maximum freezing depth of seasonal frozen ground ($p<0.01$). Gully development is primarily influenced by catchment area and elevation, while gully formation is jointly influenced by catchment area, annual and rainy season precipitation, annual average temperature, and freezing depth of frozen ground. Therefore, under the background of climate change and human activities, gullies on the Qinghai-Xizang Plateau have significant development potential, and need pay more attention to its control for protection the more precious soil resources.

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# Comparative Erodibility of UK Soils Under Different Climate Change Scenarios

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**ABSTRACT**

Climate change is increasing the frequency and magnitude of extreme rainfall events significantly increasing the kinetic energy (KE) available to breakdown and reorganize aggregates at the immediate soil surface. This has implications for soil erosion, runoff generation and flood risk. The inherent erodibility of UK soils to extreme rainfall events is currently unknown. This study quantifies the comparative erodibility of twelve UK soils subjected to an 80 mm/hr rainfall event of 5, 8, and 14 minute duration, corresponding to return periods of 5, 10, and 30 yrs, respectively. Soil textural classes investigated included sandy clay loam, sandy loam, silty clay loam, clay and clay loam agricultural soils. Air-dried sieved (<2.0 mm) soils were uniformly packed into 100 mm internal diameter and 50 mm deep PVC microcosms and subjected to the respective rainfall events. Splash detached material was collected in a 300 mm diameter concentric ring collector and post-rainfall unsaturated hydraulic conductivity ($K_{un}$) measurements made using a Minidisk infiltrometer to assess soil erosion and runoff risk, respectively.

As expected, across all soil types, the quantity of splash detached material increased with increasing storm return period indicating increased soil erosion risk. Similarly, across all soil types, increasing storm duration significantly decreased $K_{un}$ implying an increased risk of runoff generation. For the extreme 30 yr return period storm event, counter intuitively the clay soils from Westbury, Wiltshire were significantly more erodible than the sandy loam soils from Northumberland both associated with similar crop rotations. The least erodible soil was a silty clay loam from Salisbury, Wiltshire. No statistically significant correlations were observed between the mass splash detached material or $K_{un}$ and a comprehensive range of physico-chemical soil parameters investigated or soil mineralogy. These results demonstrate the highly variable response of UK soils to extreme rainfall events and highlight the need for continuing research.

**Keywords:** Climate change, extreme rainfall events, soil erodibility, erosion risk

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# Evaluation of Silt Socks and Wollastonite-Enhanced Socks in Sediment and Phosphorous Management

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**ABSTRACT**

Soil erosion is a threat to global agricultural systems, affecting top-soil integrity, crop productivity, and water quality (Liu *et al*., 2020). Agricultural runoff is a source of phosphorus pollution, driving eutrophication, algal blooms, and poor water quality (Andrade *et al.,* 2020). A current strategy for erosion management is silt socks (SS) — tubular mesh fabrics packed with dried miscanthus. The addition of wollastonite has shown promise in removing phosphorus from wastewater and agricultural runoff (Huang *et al*., 2019). The study evaluates the sediment removal efficiency of silt socks (SS) and wollastonite-enhanced socks (WS) and investigates the relationship between wollastonite particle size (Ps) and phosphorus removal efficiency. Four treatments were evaluated: soil only (control), SS, WS (1.19< Ps <2), and WS (0.50<Ps <0.71). Large bins filled with sandy loam soil were placed on a 15° slope, and a 1-hour simulated rainfall (78 mm/hour) was applied. Runoff samples were collected to measure runoff volume, dissolved phosphorus concentration, pH, electrical conductivity (EC), and sediment. Results showed that WS socks significantly improved erosion control and phosphorus retention. WS (0.50< Ps <0.7) reduced soil erosion by 94.39%± 0.02% compared to the control. Phosphorus concentration in runoff decreased by 46.47% with WS socks of a smaller particle size range compared to SS alone. This demonstrated the effectiveness of WS socks in reducing sediment and phosphorus leaching from agricultural runoff. As a part of future work, the effect of the packing density on the removal efficiency of runoff, sediment, and phosphorus is being studied. Through varying the miscanthus weight and the sock diameter, different packing densities (0.1, 0.15, 0.17, 0.2g/cm³) can be achieved.

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# Synergistic Effect of Coal Fly Ash and Polyacrylamide on Enhancing Sandy Soil's Resistance to Wind and Water Erosion

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**ABSTRACT**

Sandy soils in arid and semi-arid regions are highly vulnerable to both wind and water erosion, leading to severe land degradation and nutrient loss. This study investigated the synergistic effect of coal fly ash (FA) and anionic polyacrylamide (PAM) as amendments for enhancing the resistance of sandy soil to these dual erosion threats. Through a combination of field experiments in the sandified land in the Inner Mongolian Reach of the Yellow River and laboratory rainfall simulations, locally sourced high-calcium FA and PAM granules were thoroughly mixed with sandy soil to form a consolidated soil layer (CSL) at 0–0.3 m depth in the field and a 0.2 m amended layer under indoor conditions. The results showed that the CSL significantly reduced the wind erosion rate (WER) by up to 69% during the dry seasonal period (autumn to spring) compared to untreated control, with the 10% FA + 0.05%–0.1% PAM treatments exhibiting the most durable resistance. This improvement is attributed to the filling effect of fine FA particles and the adhesive action of PAM, which together improve soil aggregation and surface crust formation. Establishing *Achnatherum splendens* on the CSL further provided long-term stabilization, reducing the WER by 82%–92% compared to the bare CSL after 8 months, demonstrating the efficacy of a combined biochemical approach to sand fixation. Under simulated rainfall conditions (1.5 mm/min, 40 min, 10° slope), the co-application of 10%–15% FA and 0.01%–0.02% PAM altered the hydrological processes within the amended soil layer. With increasing application rates of FA and PAM, the runoff intensity increased, the time to runoff initiation shortened, and the average infiltration rate decreased. Moreover, a higher FA application rate of 15% combined with PAM resulted in a prominent increase in the cumulative sediment yield. Whereas, the 10% FA + 0.01%–0.02% PAM treatments maintained the cumulative sediment yield at a level statistically indistinguishable from untreated control. Post-rainfall analysis revealed that the amendments significantly increased water retention within the soil profile. This is due to FA increasing capillary porosity and PAM forming viscous solutions that hinder water seepage, thereby enhancing moisture availability for plants. Beyond erosion control, the FA-PAM system enhanced the soil's capacity to retain nitrogen (N). The concentrations of $NO_3^-$-N and $NH_4^+$-N retained in the soil profile after rainfall increased markedly with higher amendment rates, demonstrating a significant improvement in nutrient holding capacity. The combined use of FA and PAM created a synergistic effect that effectively stabilized the sandy soil against both wind and water erosion. This amendment can not only mitigate soil loss but also improve soil moisture conservation and nutrient retention, offering a comprehensive and sustainable solution for combating desertification and promoting ecological restoration in vulnerable sandy landscapes.

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# Tillage erosion - the blind spot in soil conservation

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**ABSTRACT**

Tillage erosion has a frequently underestimated impact on soil systems. It plays a key role in soil degradation, especially in regions dominated by large agricultural fields situated on rolling hills with short slope lengths, as typically found in former ground moraine regions in the northern US and Canada, as well as in the northern parts of Europe (e.g., northern Germany, Denmark, Poland).

It is often assumed that non-inversion tillage, as used in soil conservation systems, is associated with reduced levels of tillage erosion compared to conventional inversion tillage. Based on this assumption, non-inversion (mulch) tillage would be a method to simultaneously combat all types of erosion (water, wind, and tillage).

In this presentation, we summarise data from our own experiments, along with an evaluation of other studies that challenge this assumption. We conducted a set of paired-plot tillage erosion experiments on different slopes in Northeastern Germany, comparing a mouldboard plough with a non-inversion chisel plough while keeping tillage parameters (tillage speed and depth) constant. The study's findings demonstrate that non-inversion tillage results in a significantly higher degree of downslope soil translocation compared to inversion tillage. The soil translocation distance was found to be 1.3–2.1 times larger in cases involving non-inversion tillage. Similar results are somewhat obscured in other studies, as smaller tillage depths are often assumed when calculating erosion rates from soil translocation in the case of non-inversion tillage. However, especially in highly mechanised large-scale farming, tillage depths of non-inversion tillage often reach those of inversion tillage, while tillage speed in the case of non-inversion tends to be faster and hence even accelerates tillage erosion.

Consequently, the effectiveness of non-inversion tillage as a measure to reduce total soil erosion remains unclear., especially in regions dominated by tillage erosion. In general, tillage erosion needs to be more consistently considered in soil conservation planning.

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# Global Soil Erosion Dynamics and Drivers

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**ABSTRACT**

Soil erosion remains one of the most serious environmental problems faced globally, with direct consequences for agricultural output, food security, and the health of land ecosystems. This presentation reviews current scientific understanding of the geographic distribution of erosion and the main forces that shape it at pan-EU and Global scale, with particular attention to the combined effects of water and wind erosion, tillage, gully formation, and biomass removal. By using advanced spatial modeling methods together with large international datasets, the analysis pinpoints major areas of concern and clarifies the human and climatic pressures that intensify land degradation.

A key section of the talk reports the key finding of the Global Soil Erosion Mapping Initiative, an international collaboration that now includes 300 researchers. The initiative seeks to create high resolution, standardized, and regularly updated global maps that document visible erosion features and related degradation processes. A defining feature of this effort is its structured visual interpretation of very high resolution satellite and aerial images, which allows experts to detect and categorize erosion indicators such as gullies, sediment deposition zones, and badland landscapes. This image guided approach strengthens both the accuracy and the contextual relevance of erosion assessments, especially in complex environments or regions with limited data.

The presentation ends by considering how these findings can inform efforts to build soil resilience. This includes targeted conservation practices, sustainable land management strategies, and policy measures grounded in scientific evidence that aim to protect soil as a limited and nonrenewable resource.

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# Effects of Straw Mulch in Hillslope Longitudinal Furrows on Soil Physicochemical Properties and Erosion Resistance in the Black Soil Region of Northeast China

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**ABSTRACT**

Water erosion poses an obvious threat to cultivated land quality and grain security in black soil regions of the whole world. Straw mulch serves as an effective water erosion control measure for soil improvement as well as soil and water conservation. However, the intra-annual dynamics of soil properties and their drivers for soil aggregate stability and erosion resistance under straw mulch remain unclear. The objectives of this study were to reveal the variations and driving mechanisms in key soil properties, aggregate stability and erosion resistance by a field situ monitoring method with three straw mulch amounts (CK, no straw mulch; $MR_{50}$, 4.5 t $hm^{-2}$ straw mulch; and $MR_{100}$, 9.0 t $hm^{-2}$ straw mulch). The results demonstrated that straw mulch application in longitudinal furrows significantly enhanced soil physical properties, as evidenced by marked increases in soil moisture content (SMC), and macroaggregate (> 0.25 mm) content ($R_{0.25}$) ($P < 0.05$). Compared to the CK, the soil organic matter (SOM) content increased by 3.80 g $kg^{-1}$ and 3.85 g $kg^{-1}$ under the $MR_{50}$ and $MR_{100}$ treatments, respectively. Concurrently, soil erodibility decreased substantially, with reduction factors of 2.5 and 4.5 relative to CK under $MR_{50}$ and $MR_{100}$. Furthermore, straw mulch promoted acidification in the acidic soil, leading to a decrease in pH from 5.97 to 5.81 under the $MR_{100}$ treatment. Structural equation modeling (SEM) revealed that soil erosion resistance was driven directly by SOM, SMC, and clay content, as well as indirectly by clay content through its effects on SOM and SMC. In conclusion, straw mulch in longitudinal furrows should be promoted due to its high efficiency in improving soil properties. These findings offer insights to enhance soil erosion control and optimize straw utilization.

**Keywords:** Soil structure; Soil erodibility; Sloping farmland; Structural equation modeling (SEM); Sustainable agriculture

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# Yield decline across soil types under progressive soil erosion: Basis for soil conservation criteria in the Sudan Savanna

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## ABSTRACT

Soil erosion is one of the most serious causes of land degradation in West Africa, where large areas of cultivated land are losing productivity. Despite this, the dissemination of soil conservation practices has been slow, mainly because there are no locally adapted criteria or standards for soil conservation planning. Establishing such standards is essential for assessing soil erosion risks and guiding farmers toward appropriate management strategies from a long-term perspective. This study aimed to quantify how cumulative soil erosion, crop type, and fertilizer application affect crop yields on major soil types in the Sudan Savanna, and to develop the first soil conservation criteria in Africa that enable farmers to select suitable conservation practices according to their biophysical and socio-economic conditions.

Field experiments were conducted over three years (2022–2024) at the Saria Station of INERA in Burkina Faso, on three representative soils of the Sudan Savanna: Ferric Lixisols (LX-fr), Petric Plinthosols (PT-pt), and Pisoplinthic Petric Plinthosols (PT-pt.px), which differ in the effective soil depth for crop cultivation (LX-fr > PT-pt > PT-pt.px). To simulate cumulative soil erosion, five levels of topsoil removal were artificially applied (0, 2.5, 5.0, 10, and 15 cm). Two crops (sorghum and cowpea) were grown under fertilized and unfertilized conditions, with five replications per treatment.

The three-year average yields of sorghum in the unfertilized 0-cm removal plots were 219, 97.2, and 68.8 kg ha$^{-1}$ on LX-fr, PT-fr, and PT-pt.px, respectively, while those of cowpea were 271, 208, and 186 kg ha$^{-1}$. Yield reduction with increasing erosion depth was more pronounced in PT-pt.px, which had the shallowest effective soil depth, than in LX-fr. Sorghum was less sensitive to soil loss than cowpea on LX-fr, while fertilizer application had a stronger positive effect on PT-pt.px, where the baseline yield was lowest. Assuming an annual soil erosion rate of 2 mm yr$^{-1}$ without conservation (Zougmoré, 2003), two scenarios were modeled: (i) adoption of at least one soil conservation measure reducing erosion by 40%, and (ii) adoption of multiple measures reducing erosion by 70%. The simulation indicated that maintaining at least 80% of the current yield after 25 years would require different strategies depending soil type and crop: for sorghum on LX-fr, no action may be needed; for sorghum on PT-pt.px, fertilization or multiple conservation measures are required; for cowpea on LX-fr, either fertilization or one conservation measure is necessary; and for cowpea on PT-pt.px, multiple conservation measures or fertilization are essential.

In conclusion, we quantified yield decline rates of sorghum and cowpea under progressive soil erosion across three contrasting soil types and developed soil conservation criteria that predict long-term yield sustainability based on soil type, fertilization, and conservation effort. This represents the first attempt to establish soil conservation standards for sub-Saharan Africa, providing a framework for farmers to select feasible conservation strategies according to their field conditions and management capacity.

**Acknowledgments**

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# Study on Soil Erosion and the Spatiotemporal Distribution Characteristics of Erosion Factors in the Northeast Cinnamon Soil Region

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## ABSTRACT

Soil erosion poses a severe challenge to ecological sustainability. However, existing studies predominantly focus on total erosion estimation and conventional spatiotemporal variations, leaving a gap in understanding the spatial patterns, heterogeneity, and spatial transmission effects of driving factors at a macro scale. To address this, this study introduces the concept of "spatial marginal effects." Based on multi-source data from 2000 to 2020 across six cities, including Fuxin, and integrating Remote Sensing (RS) and Geographic Information Systems (GIS), an in-depth analysis of soil erosion was conducted. During the study period, the soil erosion modulus in the Northeast Cinnamon Soil Region exhibited phasic changes. The intensity of erosion exacerbated after 2010, peaking in 2013 at 435.67 $t \cdot hm^{-2} \cdot a^{-1}$. Time-series analysis identified 2009 and 2014 as critical turning points, reflecting significant fluctuations in erosion intensity. Notably, in 2014, the erosion status in Tongliao, Chaoyang, and their surrounding areas showed significant improvement. Between 2000 and 2020, the dominant land use types in the region were cultivated land and grassland. The total area of land use change was 12,519.34 $km^2$, accounting for 6.61% of the total study area. The changes primarily involved cultivated land and grassland. From 2000 to 2010, cultivated land area decreased slightly while grassland area increased. However, after 2010, this trend reversed: cultivated land area rebounded significantly to levels exceeding those of 2000, while grassland area declined sharply. Concurrently, areas of forest land, water bodies, and unused land decreased, whereas urban construction land increased. Both total soil erosion and its primary driving factors (rainfall erosivity, slope length and steepness, soil erodibility, and vegetation management) exhibited significant positive spatial correlations and spatial agglomeration. The Spatial Durbin Panel Data Model (SDPDM) quantified the "spatial marginal effects" of these driving factors, confirming that their influence transcends regional boundaries to produce spatial lag and spillover effects. This demonstrates that the synergistic action of driving factors within a region and in adjacent areas significantly impacts soil erosion.

**Keywords:** Northeast China Region; Soil Erosion; RUSLE Model; Spatiotemporal Characteristics; Spatial marginal effect

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# Mechanism of Surface Runoff Erosion Transport and Its Verification and Application

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**ABSTRACT**

Soil security is crucial for humanity's future, and water erosion poses a serious threat to soil security, yet research on erosion processes and mechanisms urgently needs to be strengthened. By analyzing erosion mechanisms and building mathematical models and verifying them with indoor and outdoor test data, studies on the erosion and transport processes have been conducted. The results demonstrated the energy dissipation in the process of storm runoff erosion was related to the water-sediment characteristics, the Froude number (Fr) of the storm runoff flow, the ratio of flow velocity to the initiation module velocity for erosion (V/V*c), and the square difference ratio of flow velocity and sediment friction velocity. The erosion transport equation was presented and verified with a large amount of indoor and outdoor data. Integrated this formula into SWAT resulted in an improved version, SWAT-S, which enhances sediment load calculation performance. SWAT-S was evaluated in the Yanhe River Basin of the Loess Plateau in China using the coefficient of determination ($R^2$), Nash-Sutcliffe efficiency (NSE), percent bias (P-BIAS), and ratio of root mean square error to observed standard deviation (RSR). The results indicate that SWAT-S is more successful than SWAT in simulating monthly sediment load. During calibration, $R^2$, NSE, |P-BIAS|, and RSR improved by 5.08%, 17.65%, 2.92%, and 10.00%, respectively. During validation, these improvements were 1.18%, 10.39%, 45.45%, and 18.75%, respectively. Additionally, SWAT-S overestimated sediment load by 2.66 million tons during the flood season from June to September compared to SWAT, and it better matched observed data. The above results indicate that the given equation could unify rill erosion sediment transport with channel and river sediment transport processes, and compared to famous formulas, it has higher computational accuracy. The SWAT-S improved by the formula could enhance sediment estimation performance, which is beneficial for the widespread application of the model in more global regions.

**Keywords:** Erosion Transport, Mechanism, Verification and Application, SWAT-S

**Acknowledgments**

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# Long slope erosion-deposition patterns under different tillage systems driven by multiple erosion forces in the Chinese Mollisol region

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**ABSTRACT**

The special geographic characteristics coupled with unreasonable tillage activity and coexistent multiple erosive forces (rainfall, snowmelt, and wind) induce severe soil erosion in the Mollisol region of Northeast China. However, the studies on long slope erosion-deposition patterns under different tillage systems driven by multiple erosion forces are rare. Therefore, this study was to identify the effects of flat tillage (non-ridge tillage, FT), longitudinal wide-ridge tillage (LWT), and traditional longitudinal ridge tillage (LRT) practices on the spatial patterns of long slope erosion-deposition and sediment transport along the three natural long slopes with 320 m slope length by using Rare Earth Elements (REE) tracing method during the rainfall, snowmelt and wind erosion periods. Soil erosion rates driven by rainfall, snowmelt and wind were 1678.5–2558.5 t $km^{-2}$ $a^{-1}$ for the FT, 1089.0–1468.9 t $km^{-2}$ $a^{-1}$ for the LWT and 181.9–314.4 t $km^{-2}$ $a^{-1}$ for the LRT, respectively, in which the sediment yield with the FT, LWT and LRF driven by rainfall and snowmelt accounted for 88.0 %-96.4 % of the total sediment yield. During the rainfall erosion period, the erosion regime was dominated on the slopes with these three tillage practices, whereas deposition only occurred at the slope toe. For the FT, 73.6 % of the sediment mass was deposited at the 0–120 m slope length. A total of 50.7 % of the sediment was deposited at the 0–80 m slope length with the furrows of LWT, whereas all the sediment was transported out of the entire slope with the furrows of LRT practice. During the snowmelt erosion period, a spatial pattern with erosion-deposition alternations was observed for the FT and LWT, whereas the erosion regime dominated on the slope with the LRT practice. During the wind erosion period, there were evident periodical changes with strong-weak alternations for all three tillage practices. The findings of this study served as a scientific References for implementing precise soil conservation measures for controlling compound soil erosion in the Chinese Mollisol region.

**Keywords:** Erosion-deposition; Sediment transport; Multiple erosive forces; Spatial pattern; Tillage practices; Mollisol region of Northeast China

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# Exploration of Multi-Scale Spatiotemporal Differentiation and Influencing Factors in Yuanmou County Based on SBAS-InSAR

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**ABSTRACT**

Based on SBAS-InSAR, this study obtained the deformation rate of Yuanmou County from January 2020 to October 2024. Spatially, the deformation spatial differentiation was classified into three levels: the county scale, regional scale (sedimentary area and bedrock area), and local scale (gully walls, gully beds, and slopes within both the sedimentary and bedrock areas). It was found that in terms of the mean annual deformation, there was no significant difference between gully and non-gully areas. The erosion in the sedimentary area was significantly greater than that in the bedrock area. At the local scale, erosion was highest on gully walls, followed by gully beds, and then slopes; however, the differences among these three units within the sedimentary area were relatively small. Using Random Forest and SHAP for multi-scale feature importance ranking, the results showed similar rankings across multiple scales, indicating the robustness of the findings. The main influencing factors varied across scales: elevation was the most critical factor at the county scale, soil mechanical composition was the dominant factor at the regional scale, and different factors controlled deformation at various local units. To enhance model interpretability, SHAP trend analysis was employed, which captured the non-linear relationships between key features and deformation, revealing the complexity of environmental factors' influence on deformation. Notably, the importance of NDVI exceeded that of rainfall rate at multiple scales. Temporally, the analysis revealed an increasing trend in both erosion amount and deformation magnitude in Yuanmou County. Based on the Random Forest importance ranking, NDVI showed a decreasing trend interannually, while the importance of elevation increased. The interannual changes in deformation may be related to the decrease in NDVI. Seasonally, the importance of NDVI increased during the dry season, while that of elevation rose during the rainy season, demonstrating that deformation is associated with seasonal soil moisture regulation.

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# Effects of Different Land Use Types on Soil Multifunctionality and Their Driving Mechanisms in Karst Fragile Ecosystems

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**ABSTRACT**

Elucidating the effects of different land use types on soil physicochemical properties and microbial community characteristics in karst regions, and further revealing how these factors regulate soil multifunctionality, is of great significance for ecological management in rocky desertification areas. However, the underlying mechanisms remain unclear. This study was conducted in a typical rocky desertification area in southwest China, where five land use types—cropland, grassland, shrubland, plantation forest, and secondary forest—were selected. Soil samples were collected at different depths (0–10 cm, 10–20 cm, and 20–30 cm) to systematically evaluate five key aspects of soil multifunctionality: nutrient supply, microbial growth efficiency, soil organic matter (SOM) decomposition, nutrient cycling, and plant–microbial symbiosis. The results showed that microbial growth efficiency, SOM decomposition capacity, and overall soil multifunctionality in cropland and grassland were significantly lower than those in forested lands. The surface soil of shrubland exhibited the highest soil multifunctionality, with significant variations observed across soil depths for all functions. In addition, cropland and grassland had higher bacterial α-diversity, and their bacterial and fungal community structures significantly differed from those of forested lands. Shrubland showed higher bacterial community stability and network complexity, while plantation forest displayed the highest network complexity. Driver analysis indicated that soil microbial network characteristics significantly influenced soil multifunctionality, but soil physicochemical properties had a higher independent explanatory power. Structural equation modeling further confirmed that soil organic carbon (SOC) is a key variable linking different land use types and soil depths to enhanced soil multifunctionality. These findings highlight the positive role of shrubland restoration and establishment in improving soil multifunctionality in rocky desertification areas, which can enhance the precision and effectiveness of ecological restoration and promote the transition of regional ecosystems from "degradation repair" to "functional enhancement."

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# Arbuscular mycorrhizal fungal community is vulnerable to mining activity but play key roles in runoff regulation in rare earth mining areas

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**ABSTRACT**

Vegetation damage from REE mining, compounded by intense rainfall, triggers the runoff-driven spread of contaminants and resulting ecosystem degradation. These disturbances may extend to arbuscular mycorrhizal fungi (AMF), a key plant symbiosis that influences soil structure and water infiltration; however, the extent and mechanisms of such impacts remain insufficiently understood. This study aimed to investigate the responses of AMF communities to heap leaching (HL), in-situ leaching (IL), and ecological restoration (ER), and their role in regulating runoff under simulated rainfall. Our results showed that HL and IL caused pronounced soil desertification and acidification, respectively. HL markedly reduced AMF abundance and diversity, whereas ER partially restored these attributes but did not reach levels at the Ore site (OR). Clay content, nutrient levels, and precipitation emerged as the primary drivers of AMF community variation across REEs mining areas. Inoculation with indigenous AMF enhanced ryegrass growth and hyphal abundance and effectively reduced runoff generation under simulated rainfall. Collectively, the evidence demonstrates that REEs mining activities disrupt AMF communities primarily through soil desertification and acidification, and although ER improves AMF attributes, full recovery remains limited. Indigenous AMF play a significant role in regulating runoff production, underscoring the importance of conserving and re-establishing AMF communities to support ecological restoration in REEs mining landscapes.

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# Measuring tillage and water erosion under different tillage systems in a commercial potato farm in Atlantic Canada

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**ABSTRACT**

In Atlantic Canada (AC), tillage intensity in commercial potato farms is the highest among all crops. Tillage disturbs soil, leading to both water and tillage erosion, resulting in declining soil health. In a commercial potato farm field in New Brunswick, Canada, experiments were conducted to quantify tillage and water erosion under conventional and conservation tillage. Tillage erosion was assessed with tillage translocation experiments using point tracers buried at two depths to track soil movements by tillage operations. Water erosion was assessed by measuring soil surface residue coverage and surface roughness using drone images and by rainfall simulation experiments. For primary tillage, moldboard plough (MP) moved tracers at both depths much further than chisel plough (CP). For planting, tillage translocation was at similar level to that for CP. For planting plus harvesting of potato, tillage translocation exceeded the level for MP in the primary tillage. MP resulted in significantly less Surface Coverage Raito than CP, although the values were very low for both tillage treatments. Random Roughness Index was significantly lower for CP, only 63% of that for MP. The Chain Roughness Index (CRI) was significantly lower for along than across tillage direction. CRI for CP was significantly lower, about 82% and 62% of those for MP in the across and along direction, respectively. In the rainfall simulation experiments, CP significantly increased the time to runoff initiation and infiltration by 2.7 and 2.1 times, respectively. CP also significantly reduced runoff discharge, sediment yield and Flow Weighted Mean Sediment Concentration by 53-98%, 82-99% and 35-61%, respectively. Overall, conservation tillage was found to have lower risks for both tillage and water erosion in the study field.

**Keywords:** tillage translocation, rainfall simulation, conservation tillage

# Soil Erosion in the European Union: A major threat for EU agriculture

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**ABSTRACT**

Over the past decade, the European Commission's Joint Research Centre (JRC) has refined the Revised Universal Soil Loss Equation (RUSLE) model to assess water-induced soil erosion across Europe for the References period of 2010. This updated framework, termed RUSLE2015, integrates the most recent pan-European datasets for critical input parameters, including rainfall erosivity, soil erodibility, land cover-management, topography, and support practices (Panagos et al., 2015). The model has been applied to quantify water erosion-induced soil loss for the years 2000, 2010, and 2016, with latest assessment extending to 2023. Recent analyses (Panagos et al., 2020) indicate that the mean annual soil loss from water erosion within the European Union (EU) is approximately 2.4 t $ha^{-1}$ $yr^{-1}$, representing a 9% reduction since 2000. A recent estimate for 2023 confirms the trend as soil rosion loss is declining by 4% compared to 2016 (Borrelli and Panagos, 2025) . This decline is primarily attributed to the adoption of improved soil conservation practices in agricultural systems, driven by the Good Agricultural and Environmental Condition (GAEC) standards under the Common Agricultural Policy (CAP).

Previously, a significant research gap existed regarding wind erosion due to the absence of continental-scale assessments. To address this, the JRC evaluated wind erosion susceptibility across Europe using the Revised Wind Erosion Equation (RWEQ) model (Borrelli et al., 2017). Additionally, the JRC has advanced methodologies to quantify soil loss from other non-rainfall-driven processes, including crop harvesting (Panagos et al., 2019), tillage erosion (Borrelli et al., 2023), post-fire erosion (Vieira et al., 2024), and gully erosion (Borrelli et al., 2025). These contributions have enhanced the spatial and process-based understanding of erosion dynamics in Europe, encompassing both water and wind erosion, as well as anthropogenic and landscape-specific mechanisms.

Future projections suggest a 13–22.5% increase in water erosion-induced soil loss across the EU by 2050, primarily driven by anticipated increases in rainfall intensity under climate change scenarios (Panagos et al., 2021). Under Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5, rainfall erosivity is projected to rise by 15.7–25.5%, with corresponding proportional increases in erosion rates. To mitigate these risks and inform adaptive management strategies, the EU Soil Observatory has prioritized the development of the EU Soil Erosion Modelling (EUSEM) Platform. This platform integrates advanced geospatial analytics and process-based modeling to provide high-resolution, spatio-temporal soil erosion estimates. Such data are critical for supporting EU policy frameworks, including the Soil Monitoring Law, the CAP, and the Sustainable Development Goals (SDGs), by enabling evidence-based decision-making for soil conservation and land-use planning.

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# Drainage network connectivity controls phosphorus transport and export

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**ABSTRACT**

Phosphorus losses from agricultural landscapes contribute to freshwater eutrophication and have been considered a key water quality concern in the Red River Valley of southern Manitoba, Canada., which is characterized by clay-rich Chernozemic and Vertisolic soils. Crop production mainly relies on surface drainage (i.e., man-made shallow, in-field drains) and tile drainage to remove excess water and lower the water table. A dense network of in-field surface drains, often on the order of 20-25 km per land section (~ 259ha), connects fields to ditches and streams, increasing hydrologic connectivity and the potential for phosphorus transport during erosive runoff events. Tile drainage is increasingly being adopted to manage excess water on poorly drained soils in this region, which can further increase dissolved phosphorus export under certain soil and management conditions. This study assessed the integrated effects of drainage systems (i.e., surface and tile drainage) on phosphorus transport within the soil profile and overland flow over a four-year period (2022, 2023, 2024, and 2025) in the typical landscapes of the Red River Valley in southern Manitoba. Soil and crop samples were collected over tile lines and between tile lines, as well as across surface-drained positions. Soil phosphorus status was characterized using total phosphorus, water-extractable phosphorus, and Modified Kelowna–extractable phosphorus. Runoff and associated sediment and nutrient exports were quantified at edge-of-field monitoring stations using automated samplers triggered during runoff events. A surface water retention structure receiving tile discharge was also monitored to assess tile-drain effluent water quality. Results showed that higher concentrations of TP, WEP, and MKP are found in the surface soil layers, especially in tile-drained plots. Moreover, no significant differences were observed in crop yields (canola, wheat, and soybean) between surface and tile drainage, though tile drainage led to slightly higher variability in yield. Nutrient and sediment export varied substantially across major erosive events, indicating strong event-driven nutrient loss dynamics, particularly under conditions of limited soil surface cover by crops in spring. The findings highlight the need for targeted mitigation strategies that disrupt phosphorus connectivity along the field-ditch drainage continuum (e.g., field-edge vegetated buffer strips, managed harvest of buffer and ditch vegetation to remove accumulated phosphorus in biomass, and in-field water retention structures) to reduce peak flows and trap sediment and particulate phosphorus during high-flow events.

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# Integrating Multi-Scale Soil Evaluation and Ecosystem Service Assessment for Sustainable Land Use Planning with Targeted Agri-Environmental Measures

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## ABSTRACT

Sustainable land use planning requires spatially explicit evaluation of soil and landscape properties to balance agricultural productivity with environmental stewardship. This study applies a multi -criteria soil and land evaluation framework combined with rule-based land conversion scenarios to identify opportunities for improving ecosystem services while maintaining productive capacity in agricultural landscapes. The aim of the study was to detect how to allocate land uses to increase biodiversity and pollination services, prevent water erosion with minimal reductions in crop yield. We focused on a 5 km × 5 km landscape window in Märkisch-Oderland, Brandenburg, Germany, using GIS layers of topography, soil properties, land use, meteorological data, and multispectral satellite imagery. NDVI-derived soil productivity estimates were used as the primary indicator of arable potential, while InVEST models assessed soil erosion and pollination services.

Marginal arable land was identified using integrated indicators oflow soil productivity, slope-driven erosion risk, and landscape position, representing areas with limited capacity for stable crop yields.

Four scenarios converted these marginal areas into grassland buffers, flower strips, or mixed arrangements to evaluate trade-offs among soil conservation, habitat provision, and arable production. Results indicate that grassland buffers reduce mean soil erosion from 5.93 to 4.61 t ha_¹ yr_¹, while flower strips increase pollinator abundance by 50 % in pollinator-dependent crops. Mixed placements improve habitat richness and provide a balanced enhancement of multiple ecosystem services with minimal loss of productive area. These findings demonstrate how GIS-based soil and land evaluation and spatially targeted land use planning can optimise soil function, ecosystem services, and agricultural productivity simultaneously. The study provides a practical framework for integrating soil and landscape assessment into sustainable land management strategies, offering actionable guidance for policymakers and farmers to support resilient agroecosystems.

**Keywords:** soil evaluation, land use planning, ecosystem services, sustainable productivity, agri -environmental schemes

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# A Half-Century Intensification of Lateral Carbon Transfer along the Congo Basin's Land–Ocean Aquatic Continuum

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## ABSTRACT

The Congo Basin, home to the world's second largest tropical rainforest and river network, plays a crucial role in the global carbon (C) cycle. However, rapid population growth and land-use changes are intensifying geomorphic and biogeochemical disturbances. Consequently, the basin is experiencing accelerated soil redistribution, whose impacts on lateral C transfer along the land–ocean aquatic continuum (LOAC) remain largely unknown. By integrating the most comprehensive observation dataset available with a state-of-the-art land surface model (ORCHIDEE-$C_{lateral}$), this study quantified the magnitude and temporal evolution of lateral C fluxes in the forms of particulate organic carbon (POC), dissolved organic carbon (DOC), and carbon dioxide ($CO_2$) over the past five decades, and assessed the impact of these lateral C transfers on the terrestrial C budget.

The calibrated ORCHIDEE-$C_{lateral}$ model explains 73%, 84%, 78%, and 84% of the spatial variation in observed river water discharge, sediment discharge, POC concentration, and DOC concentration in the Congo River network, respectively. It also captures well the seasonal variations in riverine water discharge, sediment discharges, water surface extent, and riverine $CO_2$ partial pressure. Using the calibrated model, we reconstructed the historical evolution of C fluxes and transformations along the LOAC. Since 1970, lateral C (i.e., POC, DOC, and $CO_2$) input from land to river has increased significantly (Mann–Kendall $P < 0.001$), with POC, DOC, and $CO_2$ rising by 51%, 20%, and 29%, respectively. The increase in POC is primarily driven by land-use change, followed by climate change and rising atmospheric $CO_2$. Of the terrestrial C entering the Congo River network, 61% of DOC and 67% of POC remain within the river–floodplain complex—approximately two and three times the proportion retained in the Amazon and European river networks, respectively. These results suggest that the majority (> 60%) of the laterally transported terrestrial C is stored or transformed inside the Congo Basin rather than being exported to the ocean or released to the atmosphere. With the projected rapid population growth and land-use expansion in the Congo Basin, lateral C fluxes along the LOAC are expected to intensify further, reinforcing the Congo Basin's role as a major inland C buffer that reshapes the regional land–ocean C balance.

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# Check dams as a major terrestrial sink for eroded sediment and organic carbon on the Chinese Loess Plateau

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**ABSTRACT**

Lateral transfer and deposition of terrestrial organic carbon (OC) represent a critical but poorly constrained component of the global carbon cycle, largely because OC burial in dryland depositional environments remains insufficiently quantified. While substantial progress has been made in understanding OC sequestration in aquatic systems, the fate of eroded OC deposited on land is still unclear. Here, we assess sediment retention and OC burial by check dams on the Chinese Loess Plateau, a region characterized by extreme soil erosion and the highest density of check dams worldwide. Using extensive field surveys combined with remote sensing analyses, we provide a large-scale, observation-based estimate of sediment and OC sequestration by these structures. We show that 50,226 active check dams intercepted 10.2 ± 0.6 Pg of eroded sediment between 1970 and 2020, equivalent to approximately 46% of the sediment load historically delivered by the Yellow River, once the world's largest fluvial sediment source to the ocean. Based on 86 deep sediment cores, we estimate that check dams buried a total of 21.6 ± 9.9 Tg of OC over the past five decades, corresponding to an average burial rate of 468 g C $m^{-2}$ $yr^{-1}$—nearly an order of magnitude higher than that reported for global lakes and reservoirs. Moreover, the OC burial efficiency of check dams (~80%) is substantially higher than that of most other depositional environments, indicating effective long-term stabilization of eroded carbon. Given the widespread use of check dams for erosion control across dryland regions worldwide, our findings identify check dams as a previously underappreciated terrestrial carbon sink that should be explicitly incorporated into regional and global carbon budgets.

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# Research on key algorithms for global erosion topographic factor extraction

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**ABSTRACT**

Topography is an important factor affecting soil erosion and is measured as a combination of the slope length and slope steepness (LS-factor) in erosion models, such as Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), and Chinese Soil Loss Equation (CSLE), etc. However, global high-resolution LS-factor datasets have rarely been published. Challenges arise when attempting to extract the LS-factor on a global scale, specifically the limited coverage of the Shuttle Radar Topography Mission (SRTM) beyond 60°N latitude, the presence of mixed noise artifacts within raw elevation data, and the systematic errors introduced by projecting spherical geodetic coordinates onto planar systems during calculation. This study establishes a comprehensive framework to generate a new global 1-arcsecond LS-factor dataset (DS-LS-GS1) by integrating improved data preprocessing with a novel calculation algorithm. First, to enhance data accuracy, we apply an adaptive low-rank group sparse model based on edge preservation (ALGS_EP). This denoising algorithm addresses the mixed noise inherent in SRTM data by leveraging gradient constraints, successfully removing 97.6% of random and stripe noise while preserving essential terrain structure. Second, to construct a seamless global digital elevation model (DEM), we propose a topographic relief fitting mosaic method (TRF-60). This method utilizes heuristic breadth-first elevation fitting order search and adaptive local topographic relief fitting algorithm to eliminate seamlines when mosaicking SRTM with quasi-global DEMs at high latitudes, ensuring consistent topographic continuity. Based on a seamless, denoised global DEM, we developed an improved method to estimate the LS-factor. This method calculates slope gradient and slope length directly from geographic coordinates (longitude and latitude), eliminating the need for projection transformation (termed LS-WPC). Using this method, we produced a global 1-arcsec resolution LS-factor dataset (DS-LS-GS1) and integrated the algorithm into a software tool (LS-Tool). The LS-WPC method recalculates the value of each grid cell size and updates the corresponding slope steepness and slope length computation equations. This method avoids the error caused by projection at the global scale. Validation of the Himmelblau–Orlandini mathematical surface shows that errors are less than 1%. We assess the LS-WPC method on 20 regions encompassing 5 landform types, and $R^2$ of LS-factor are 0.82, 0.82, 0.83, 0.83, and 0.84. Moreover, the computational efficiency can be enhanced by up to 25.52%. DS-LS-GS1 can be used as high-quality input data for global soil erosion assessment.

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# A topographic relief fitting mosaic method for eliminating seamlines of the SRTM and additional quasi-global DEM mosaics at 60°N latitude

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**ABSTRACT**

The Shuttle Radar Topography Mission (SRTM) 1 arc-second is a quasi-global digital elevation model (DEM) of excellent quality that has undergone multiple revisions, including addressing data gaps, filling voids, and flattening water, and is always applied to worldwide terrain analysis, such as topographic mapping and disaster management. As SRTM has no data collection at latitudes above 60°N, it is necessary to expand SRTM coverage by introducing additional quasi-global DEMs of those areas. This extended process completes the SRTM and other DEM mosaics at 60°N latitude. Unfortunately, because multi-source DEMs have non-negligible elevational differences, seamlines can be easily observed and existing mosaic methods cannot eliminate seamlines, which may result in unnatural topographic relief. This study proposes a topographic relief fitting mosaic method (TRF-60) that conforms to the natural SRTM terrain. TRF-60 uses a heuristic breadth-first elevation fitting order search from seamlines to determine the mosaic order of grids and then obtains a suitable blending elevation value of each grid in the mosaic output using an adaptive local topographic relief fitting algorithm. By designing heuristic mosaic conditions consistent with local slope changes, it takes further advantage of the continuity within neighborhoods to use a heuristic breadth-first search instead of row-column traversal. Within a heuristic breadth-first search, DEMs are partitioned into six-level regions by constraining the slope and decomposing the mosaic problem into mosaic subproblems in regions with similar topographic features. This study devised an adaptive algorithm to calculate mosaic elevation blending weights on different landforms, while maintaining the local flow directions. In addition, this study smoothed the slope-constrained region edges to avoid new seamlines. Compared with the first and last (FL), weighted average (WA), and feathering-based blending (FBB) methods, TRF-60 not only solves the seamline problem, but also obtains the best representation of elevation, slope, contour, and river networks. In addition, the SRTM and Advanced Land Observing Satellite (ALOS) world 3D-30 m (AW3D30) mosaics (SAMs) exhibited more consistent terrain details and denser contours. The SRTM and Copernicus DEM mosaics (SCDMs) have a higher accuracy and express more natural contours and river networks. Overall, the SCDMs had better data quality. TRF-60 exhibits a smooth transition of elevation values in the multi-source DEM mosaic and provides a quality solution for similar mosaic problems.

# Long-Term Dynamics and Driving Mechanisms of Wind Erosion Across China (2001–2024)

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## ABSTRACT

Wind erosion is a major driver of land degradation in arid and semi-arid regions of China, yet large-scale assessments are often limited by simplified representations of vegetation cover. Most existing wind erosion models focus primarily on photosynthetically active vegetation, potentially underestimating surface protection during dormant seasons when non-photosynthetic components, such as standing residues and litter, remain effective.

To address this limitation, this study enhances the Revised Wind Erosion Equation (RWEQ) model by explicitly incorporating both photosynthetic and non-photosynthetic vegetation fractions into a unified vegetation protection framework, derived using a linear spectral unmixing approach. Based on this improved model, national-scale wind erosion dynamics across China from 2001 to 2024 were reconstructed at fine spatial resolution.

The results reveal pronounced spatial heterogeneity and strong seasonal variability in wind erosion intensity. Erosion hotspots are primarily concentrated in arid and semi-arid dryland regions, with the highest erosion rates occurring during periods of limited green vegetation cover. The mean annual wind erosion across China was estimated at 2.16 t $hm^{-2}$, and statistically significant declining trends were detected over 49% of the national land area. Over the past two decades, a general reduction in wind erosion risk is observed across much of China, particularly in regions influenced by ecological restoration and land management programs.

Further analysis indicates that atmospheric conditions, especially wind-related factors, dominate the interannual variability of wind erosion at the national scale. Vegetation recovery plays a critical moderating role by enhancing surface protection and reducing erosion susceptibility, whereas soil moisture exhibits a comparatively weaker influence. By more accurately representing seasonal vegetation structure, this study provides a refined assessment of wind erosion processes and offers useful insights for evaluating ecological restoration outcomes and supporting climate-adaptive land management strategies.

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# Mapping and Analysis of the Global Soil Erodibility Factor (K)

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**ABSTRACT**

The soil erodibility factor (K) is the main data required for large-scale soil erosion investigation and mapping using soil erosion models. For soil erosion evaluation at the slope scale, the erodibility factor (K) can be directly quantified through field measurements from a unit runoff-plot. In watershed and regional-scale soil erosion assessments, the soil erodibility factor is commonly estimated and mapped by employing soil property data and soil erodibility models. Currently, there are four models commonly used for calculating regional soil erodibility factor, including the K-factor algorithm proposed by the Universal Soil Loss Equation Handbook (USLE-K), the K-factor algorithm proposed by the Revised Universal Soil Loss Equation Handbook version 2 (RUSLE2-K), the K-factor algorithm proposed by the Erosion Productivity Impact Modeling (EPIC-K), and the K-factor algorithm based on the Deometric Mean Diameter-based model (Dg-K) proposed by Römkens. However, it remains to be studied which algorithm is more suitable to calculate soil erodibility factor (K) in the global scale. While, soil erodibility factor (K) is mostly calculated based on soil physical and chemical property data, which does not involve the content of rock fragments in these algorithms. The influence of rock fragments and their distribution difference on soil erosion requires further study. In this study, USLE-K, RUSLE2-K, EPIC-K and Dg-K algorithms and SoilGrids v2 data released by ISRIC were used to estimate the global soil erodibility factor (K) and generate a K map with 250m resolution, and analyze the spatial pattern, hotspot areas and main controlling factors of the estimation results. The measured data of soil erosion factor (K) were retrieved by literature search, and the data of 106 points, 1868 runoff plots and 12181 plot years were collected. The measured database of K factor value was established. The applicability of the four algorithms mentioned above was then analyzed, and their estimated values were tried to be modified. Then the USLE-K algorithm was taken as an example to calculate the effect of rock fragments in the soil profile and rock fragments on the soil surface. The results showed that (1) The spatial patterns of global K factors estimated by the USLE-K, RUSLE2-K, EPIC-K and Dg-K models are similar, showing that values are higher in the Northern Hemisphere than in the Southern Hemisphere, within the Northern Hemisphere, values are greater in the mid-latitudes compared to the low and high latitudes. However, the estimation results of various algorithms are different in the statistical distribution value. (2) Comparing to 106 measured values, the mean value of the result estimated by RUSLE2-K is the closest to the measured K factor, which is related to the comprehensive consideration of soil property factors in RUSLE2-K algorithm, and the modification of soil texture and soil structure index algorithms by RUSLE2-K algorithm. This is followed by the USLE-K algorithm and the EPIC-K algorithm, while the estimated K by Dg-K algorithm is quite different from the measured K factor. (3) The "hotspot" areas (HH type) with high K-factor values are concentrated in regions such as China, Russia, India, Germany, the United Kingdom, and Sweden, while the "coldspot" areas (LL type) with low K-factor values are concentrated in Brazil, Mexico, the Republic of the Congo, Zambia, Australia, and other locations.(4) Based on the importance of various soil attributes to K-factor values obtained through random forest regression, it was found that silt content has the greatest influence on the K-factor, followed by organic matter content, clay content, and structural class, whereas sand content and textural class have relatively minor effects on the K-factor. (5) The presence of rock fragment in the soil profile increased the global soil erodibility factor by 2.84%. The rock fragment on the soil surface of the mountain land and desert/Gobi reduced soil erodibility by 18.7%, the combined effect reduced soil erodibility by 6.98%. The dampening effect of rock fragment on K primarily occurs in mountainous areas with weak soil development and more rock fragment cover, as well as in soil types characterized by higher rock fragment cover. This study made the calculation of K more complete and accurate, and is of great significance for improving the accuracy of regional soil erosion estimation and promoting the scientific level of global soil erosion mapping. An earlier version of this research data was made available to the FAO Global Soil Erosion Mapping Group in 2019, and the K-factor data product, which is continuously revised based on the revision of the calculated parameters, is also available for related studies.

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# Gully runoff is the primary factor triggering gravity erosion: A case study in the Top Ten Tributaries Watershed, China

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**ABSTRACT**

Clarifying the effects of rainfall and runoff on the types and scales of gravity erosion in gullies is fundamental to establishing soil erosion control measures in compound erosion areas. Based on field observations in the North Second Gully of Baijiaqu (NSGB), the types and scales of gravity erosion in gullies and their correlations with rainfall and runoff in the hilly region of The Top Ten Tributaries Watershed (TTTW) were analyzed. (1) Gully runoff was the primary factor triggering newly occurred gravity erosion in 2025. Among the 25 newly occurred gravity erosion events observed that year, 24 events were triggered by gully runoff. (2) Gravity erosion induced by gully runoff primarily occurred as translational landslides. Among these gravity erosion events, 14 events were identified as translational landslides. (3) The main runoff direction of gully runoff influences the development types of gravity erosion. Collapses frequently occur on concave banks directly facing the runoff, while landslides are more likely on convex banks oriented away from the runoff. In the study area, gully runoff is not only the main driver for triggering gravity erosion but also a key factor in shaping its spatial distribution and types. It is recommended to strengthen runoff regulation in gullies of the TTTW to mitigate gravity erosion risks on gully sidewalls during extreme rainfall.

**Keywords:** The Top Ten Tributaries Watershed, Hilly region, Gravity erosion, gully runoff, Field observation

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# Differences in water erosion between intra-row and inter-row positions of maize in sloping farmland

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**ABSTRACT**

Maize row planting creates distinct intra- and inter-row zones with horizontally varying rainfall and root distributions. How such variability impacts horizontal distributions of water erosion remains unclear. This study examined horizontal distributions of rainfall, soil erosion, and runoff in intra- and inter-row zones through simulated rainfall experiments on sloping maize farmland during the period of full canopy development in the black soil region of Northeast China. Intra-row zones received more rainwater (averaging 60.5% of total rainfall, comprising 43.5% stemflow and 17.0% throughfall) than inter-row zones (receiving only 31.2% throughfall). Nevertheless, intra-row erosion comprised 11.7–27.0% of total sediment loss, whereas inter-row zones generated 73.0–88.3%. Runoff depth did not differ significantly between zones, but intra-row runoff coefficients were markedly lower (mean = 0.35) than inter-row coefficients (mean = 0.68). Net rainfall drove intra-row erosion, with stemflow explaining significantly more variability ($R^2$ = 0.53) than throughfall ($R^2$ = 0.07). However, inter-row rainfall erosivity originated solely from throughfall and was stronger than intra-row rainfall erosivity. Soil erosion resistance did not differ significantly between zones, indicating the erosivity of redistributed rainfall, not inherent soil erodibility, drove horizontal variation in erosion. Intra-row soil infiltration and saturated hydraulic conductivity were significantly higher and associated with greater root mass density, which promoted rainwater infiltration and reduced runoff conversion. These findings confirm inter-row zones as hotspots for water erosion owing to their higher redistributed rainfall erosivity and lower soil infiltration capacity. Targeted conservation measures, e.g., improving infiltration or applying inter-row ground cover, are crucial for reducing water erosion in sloping maize farmland.

**Key words:** Soil erosion; Runoff; Rainfall redistribution; Mollisol; Row scale

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# Hydromechanical Drivers at Raindrop Scale Underpin Soil Erosion Resistance Driven by Carbon

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## ABSTRACT

Soil organic carbon is known to enhance the stability of aggregates against slaking, slumping and erosion, but quantitative measures of hydromechanical drivers at aggregate scale are lacking. Using hydrological and mechanical measurements at raindrop size, this study quantified erosion and structure collapse mechanisms. It used a sandy loam soil from a >10-year-old field experiment that received either no organic amendment (control) or 200 t $ha^{-1}$ compost. Erosion properties were measured over 30 and 60 minutes of simulated rainfall events on soil cores filled only with undisturbed soil aggregates 5mm in diameter. X-ray µCT quantified structure collapse and porosity changes. On aggregates and the surface of the packed cores, mechanical measurements of hardness and elasticity were obtained with a 3 mm spherical loading indenter. With the same samples, hydrological measurements of water sorptivity and repellency used a miniaturized infiltrometer device with a 1.2-mm tip radius. Carbon amendement did not affect water stable aggregates. However, the underpinning mechanical and hydrological drivers of soil stability differed. The aggregates used to the pack the cores had 14% greater ethanol sorpitivity and 17% greater repellency for compost compared to control treatments. At airdry aggregates the compost reduced soil hardness and elasticity by 52% and 56%, respectively. Under fast vetting-moisutre level, compost resulted 32% greater hardness then control.After 60 minutes simuilated rainfall, control soils exhibited 32% greater surface slumping and a 29% greater reduction in total porosity than compost-amended soils. Infiltration of the rainfall was similar between treatments after 30 minutes but was slightly increased in compost-amended soil after 60 minutes. The marked structural collapse observed in the control soil coincided with pore network degradation and surface aggregate dispersion-sedimentation, reflecting reduced aggregate stability and diminished water infiltration under erosive stress. Splash sediment and surface roughness was similar between treatments at post 30- and 60-minutes rainfall. Soil mechanical properties were driven by organic carbon and very sensitive to moisture levels. Soil hardness and elasticity were significantly higher at airdry moisture level but under fast vetting-moisture level the values changed, and compost-amended soil was harder than control which exhibit greater resistance to deformation. The findings confirm that compost-derived carbon resisted erosion by mechanical stabilization, decreasing pore structure collapse at the aggregate scale under rainfall erosive stress. These first ever raindrop scale hydrological and mechanical measurements demonstrate the fundamental role of organic carbon in maintaining aggregate structural resistance against erosion.

**Keywords:** Soil erosion, Structure collapse, Organic carbon, X-ray µCT, Hydromechanical drivers.

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# Regional Soil Erosion Survey and Mapping in the Pre-GIS Era : Research Progress, Scientific Contributions, and Contemporary Implications

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**ABSTRACT**

**S**oil **e**rosion **m**apping (SEM) is both a critical methodology and a core topic in the field of regional soil erosion research. From the mid-1920s to the late 1990s, a period referred to here as the "pre-GIS era", when remote sensing and GIS technologies were not yet widely used in SEM, a number of countries and international organizations carried out systematic researches and mapping practices on soil erosion surveys and mapping at national and even global scales. They included the United States, the former Soviet Union, China, Australia, FAO, etc. These efforts led to the development of soil erosion classification systems. The resulting soil erosion maps established an ontological framework for large-area soil erosion studies, provided valuable historical baseline and contextual information for research on dynamic processes of regional soil erosion, and laid the foundation for classical paradigms in regional soil erosion mapping. Furthermore, these cartographic achievements have exerted a profound historical influence and continue to have a sustained practical significance in various aspects. These include legislation, the institutional development of soil and water conservation, the establishment of regional or national soil erosion monitoring systems, and the advancement of global soil and water conservation initiatives. Nevertheless, these pioneering studies and map products have received less attention recently and are increasingly at risk of being overlooked, becoming "a Sleeping Beauty". This paper focuses on major achievements in soil erosion surveying and mapping during the pre-GIS era. It examines representative cases and historical contexts, summarizes their scientific contributions and societal impacts, and explores their implications for the development of contemporary digital soil erosion mapping, with the aim of promoting continued innovation and academic continuity in this field.

**Keywords:**Soil Erosion Mapping, Pre-GIS Era, Soil and Water Conservation, Soil Erosion Mapping, Ontology, Historical Baseline

# Study on the Hydrodynamic Threshold of Soil Erosion Regulated by Vegetation on the Hilly-Gully Complex Slopes of the Loess Plateau

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**ABSTRACT**

On the slopes of the loess hilly region, the interaction between vegetation coverage and spatial distribution dominates hydrological connectivity, thereby altering the runoff and sediment yield threshold and the balance process of infiltration-runoff partitioning, and ultimately affecting the erosion reduction efficiency of vegetation configuration projects in this area. Although there is a consensus on the enhancing effect of vegetation on the hydrodynamic threshold of soil erosion, previous studies have mostly regarded vegetation as a homogeneous coverage factor, ignoring the key role of its spatial pattern. Based on in-situ controlled runoff scouring experiments in runoff plots of the Chaigou Watershed on the Loess Plateau, this study aims to reveal the regulatory mechanism of vegetation spatial configuration on soil erosion and sediment yield on hilly-gully complex slopes. The erosion responses under different vegetation coverage (25%, 50%, 75%) and three typical vegetation distribution patterns (vegetation located on the upper, middle, and lower parts of the hilly slope) were systematically quantified at multiple flow rates (12, 16, 20 L/min). Firstly, the piecewise regression model was used to accurately identify the critical hydrodynamic threshold where the soil erosion rate undergoes an abrupt change. Secondly, the theories of energy dissipation and entropy change were introduced to clarify how different vegetation patterns alter the flow energy structure. Finally, the Generalized Additive Model (GAM) combined with SHAP (SHapley Additive exPlanations) interpretability analysis was used to quantitatively analyze the nonlinear effects and relative contributions of vegetation coverage, spatial distribution, and runoff intensity on erosion and sediment yield. The results showed that there is a critical abrupt threshold driven by hydrodynamic conditions in the erosion process of the complex slopes in the loess hilly region. When the Reynolds number (Re) and runoff depth of the runoff exceed 428.84 and 1.05 cm, respectively, the slope sediment yield rate increases sharply. Meanwhile, the specific conditions triggering the threshold exhibit a strong dependence on the vegetation spatial pattern: under high coverage (75%), the critical flow shear stress (τ) required for sediment initiation on the complex slope reaches its peak when vegetation is arranged on the upper part of the hilly slope, while the critical Froude number (Fr) and runoff depth (FD) decrease from the top to the bottom of the slope. The spatial differentiation of the above thresholds originates from the difference in energy dissipation mechanisms: vegetation arranged on the upper part of the hilly slope exhibits an effective source blocking effect, maintaining the low-entropy ordered state of the complex slope; however, under extreme hydrodynamic conditions, the single arrangement of vegetation on the lower part of the hilly slope leads to high system entropy in the medium to high vegetation coverage range (50%-75%). Therefore, the erosion stability of the hilly-gully complex slope is dominated by the vegetation layout at key slope positions. Identifying and optimizing the vegetation configuration at key nodes is conducive to the precision scientific regulation of soil and water conservation projects in arid and semi-arid regions.

**Key words:** soil erosion and sediment yield; vegetation pattern; threshold; loess hills-gully composite system

**Acknowledgments**

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# Coupled Wind-Rain Forcing Alters Runoff Generation and Soil Loss Dynamics Across Soil Surface Conditions

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## ABSTRACT

Soil erosion results from complex interactions among climatic drivers and soil surface properties, yet erosion processes are commonly assessed under rainfall-only and wind-only conditions. In particular, the role of wind–rain coupling and its interaction with soil surface roughness remains poorly represented in erosion studies and predictive frameworks. This study examines how wind-driven rain modifies hydrological response and soil detachment processes under contrasting soil surface roughness conditions.

Controlled experiments were conducted using a coupled rainfall-wind simulation system to apply windless and wind-driven rainfall events at increasing wind velocities on sandy loam soils. Rainfall characteristics were measured under both calm and windy conditions. Time-to-runoff, time-to-infiltrate, runoff and infiltrate volumes, splash erosion, and sediment transport were quantified on initially smooth and rough surfaces under windless and wind-driven rainfall conditions. Changes in soil surface morphology were assessed before and after each rainfall event to evaluate surface feedback induced by wind-rain forcing.

Results show that wind-driven rain fundamentally alters runoff and soil loss mechanisms by increasing rainfall kinetic energy, accelerating runoff onset, and amplifying soil loss compared to windless rainfall. While rough soil surfaces moderated runoff and sediment export at lower wind velocities, their buffering capacity diminished under stronger wind velocity, leading to soil and water losses comparable to or exceeding those observed under windless rainfall. In addition, wind-driven rain amplified soil surface roughness changes, increasing roughness on initially smooth surfaces while reducing roughness on pre-roughened soils, thereby extending these contrasting roughness responses previously observed under rainfall-only conditions (Bahddou et al., 2023).

These findings demonstrate that erosion response is governed not only by rainfall characteristics but also by the interaction between wind velocity and initial soil surface condition. Incorporating wind-rain coupling and dynamic soil surface states into erosion assessments is therefore essential for improving erosion prediction and for designing effective soil and water conservation strategies under changing climatic conditions.

**Keywords**

Erosivity, Runoff, Soil loss, Wind-driven rain.

**Acknowledgments**

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**References**

Bahddou, S., Otten, W., Whalley, W.R., Shin, H.C., El Gharous, M., Rickson, R.J., Changes in soil surface properties under simulated rainfall and the effect of surface roughness on runoff, infiltration and soil loss, *Geoderma,* 431 (2023) 116341.

# The response mechanism of organic carbon loss on loess slopes to the process of soil erosion

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**ABSTRACT**

Understanding the dynamics of soil organic carbon (SOC) loss in eroding slope is essential for assessing the role of soil erosion in the terrestrial carbon cycle. However, a systematic theoretical framework explaining how erosion processes influence SOC loss is still lacking. This study integrates $^{7}$Be tracer technology, in-situ runoff plot monitoring, and field/laboratory simulated rainfall experiments to examine variations in SOC content, enrichment, and fractionation within sediments produced by splash, inter-rill, and rill erosion, as well as in surface soils at the erosion interface. Key controlling factors—including slope gradient, slope length, vegetation cover, and rainfall characteristics—were evaluated to identify determinants of SOC dynamics and to elucidate the response mechanisms of slope SOC loss to soil detachment, transport, and deposition. Results indicate that mineral-associated organic carbon (MOC) is the dominant form of SOC loss across all erosion stages, substantially exceeding particulate organic carbon (POC) losses. Elevated loss rates occurred under high rainfall intensity (120 mm·h$^{-1}$, 20° slope), high raindrop kinetic energy (>168.4 J·hm$^{-2}$), longer slopes (>14 m), low vegetation cover (<35%), and extreme rainfall events. Fine particles, particularly clay and silt, were identified as the primary carriers of MOC. As rainfall intensity, slope gradient, length, and energy increase, fine particles migrate increasingly as aggregates, altering the distribution of SOC fractions and enhancing MOC accumulation. In contrast, vegetation cover reduces clay enrichment in sediments, indirectly attenuating MOC loss. Rainfall (intensity and kinetic energy) and topography (gradient and length) regulate erosion intensity (sediment yield), drive particle sorting (enrichment of fines), and ultimately govern the preferential transport and enrichment of MOC. Vegetation counteracts this process via physical interception and improved soil stability, thereby mitigating SOC loss. These findings provide a basis for further mechanistic studies on slope SOC loss and clarify the effects of erosion on soil carbon stock dynamics, carbon budgeting, and the development of process-based carbon cycling models.

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# Interactive Effects of Vegetation Configuration and Rainfall Characteristics on Runoff and Sediment Yield in the Ridge-Gully Slope System of the Loess Hilly-Gully Region

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**ABSTRACT**

Vegetation restoration is an important measure for controlling soil and water loss on the Loess Plateau. However, within the typical ridge-gully slope system, the interactive response mechanisms of runoff and sediment processes to natural rainfall characteristics and vegetation spatial patterns remain to be systematically elucidated. Based on ten in-situ runoff plots established in a representative small watershed of the Loess Hilly-Gully Region, long-term monitoring of erosive rainfall events was conducted, and the soil and water conservation benefits of nine vegetation configuration schemes (20%, 50%, and 75% coverage combined with upper, middle, and lower slope positions) were systematically evaluated relative to bare slopes. The results indicate that erosive rainfall in the study area can be classified into three types. Among them, Type II rainfall (high volume, long duration, low intensity) is the primary contributor to soil and water loss, accounting for 61.58% and 64.97% of total runoff and sediment yields, respectively, and exhibiting erosion characteristics dominated by total runoff volume. In contrast, Type I rainfall (short duration, high intensity) triggers the most intense erosion processes, with the highest average sediment concentration, representing a mode dominated by erosion intensity. Overall, the sediment reduction efficiency of vegetation measures (up to 68.59%) is significantly higher than their runoff reduction efficiency (up to 40.44%). Moreover, vegetation spatial configuration exerts a significant influence on regulation effectiveness, with configurations located on the lower ridge-gully slope demonstrating superior soil and water conservation functions. Under Type II rainfall conditions, which contribute most to erosion, the configuration with 75% vegetation coverage on the lower slope reduced runoff and sediment by 59.1% and 79.8%, respectively, compared with bare slopes. In addition, with increasing vegetation coverage, the sediment-runoff relationship gradually shifts from a linear form to a nonlinear form with a power exponent greater than 1, indicating that vegetation plays an important role in regulating the slope erosion resistance threshold. These findings provide a quantitative basis for the coordinated optimization of vegetation structure and function in restoration practices on the Loess Plateau.

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# A Framework for Global Soil Erosion Mapping（GSERmap）

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**ABSTRACT**

**【Background and Significance】** Soil erosion has long been a persistent problem and will continue to be a major global ecological and environmental issue, posing a serious threat to sustainable economic development, ecosystem integrity, and global food security. A global inventory of soil erosion has been produced through the Global Assessment of Soil Degradation (GLASOD) launched in 1987 under the United Nations Environment Program. However, over recent decades, global climate warming and increasingly intensive human activities have substantially altered both the severity and spatial distribution of soil erosion worldwide. To support the 2030 United Nations Sustainable Development Goals (SDGs) and reduce information disparities among countries, the Food and Agriculture Organization (FAO) initiated the country-driven Global Soil Erosion Map (GSERmap) project, aiming to update the global soil erosion inventory using the most recent data and appropriate models and methodologies.

**【Objectives】**The objectives of the GSERmap project are to: (1) develop a relatively harmonized and integrated technical framework for global soil erosion investigation, assessment and mapping；(2) produce a series of global soil erosion maps and databases covering water erosion, wind erosion, and tillage erosion；(3) establish a foundation for long-term, dynamic monitoring and mapping of global soil erosion; and(4) enhance capacity for soil erosion monitoring, assessment, and decision-making at both global and national levels, particularly in developing countries.

**【Implement Procedures】** The GSERmap project will be implemented through international collaboration with peer experts, adopting a country-driven approach. The project will be carried out in three phases. Phase I will focus on integrating the technical system for global soil erosion mapping and establishing an information-sharing platform. During this phase, the *Technical Specifications and National Guidelines* will be developed and refined through pilot studies on soil erosion surveys and mapping in selected countries, and a basic global database of biophysical soil erosion factors will be established. Phase II will emphasize the collection of human-induced erosion factors using "sampling survey" techniques, integrating high-resolution remote sensing imagery with field investigations. Phase III will concentrate on global soil erosion assessment and mapping using model-based approaches, followed by validation and iterative revision.

**【Acknowledgments】** The authors would like to express their sincere gratitude to contributors from FAO/GSP, China, ERC, the United States, Canada, Italy, Australia and Japan.

**Keywords:** Global Soil Erosion Mapping, GSERmap; FAO; Land degradation; SDGs; Soil and Water Conservation.

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# Improving Global Rainfall Erosivity by Using Regional Achievements

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**ABSTRACT**

Accurate estimation of global rainfall erosivity is essential for reliable assessments of global soil erosion. The most widely used global rainfall erosivity map was derived from 1–60 minute precipitation records at ~6,000 stations, using a single globally uniform conversion factor to translate coarse to fine temporal resolution data. However, large, spatially variable uncertainties compromise its reliability among regions, due to the highly uneven distribution of gauges and the scarcity of local validation data. In this study, the existing global map is refined using daily and hourly rainfall datasets from a much denser and more uniform station network. By systematically comparing these daily- and hourly-based estimates with published, high- accuracy regional rainfall erosivity studies, we adjust the global product to better reflect regional conditions. The resulting map provides a more robust basis for global soil erosion assessment and for evaluating the impacts of climate and land-use change on soil degradation.

**Keywords:** Global Rainfall Erosivity; Data Precision; Regional Calibration; Soil Erosion Assessment

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# Global-Scale Mapping of the Non-Agricultural Cover-Management Factor (Cnon-crop) for Soil Erosion Modelling

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**ABSTRACT**

Vegetation cover is a key factor regulating soil-erosion processes, and high-precision mapping of vegetation conditions is essential for improving regional soil-erosion assessment. The Universal Soil Loss Equation (USLE) and its revised version (RUSLE) remain the most widely used empirical models for predicting soil-erosion rates at regional and global scales. Within these models, the effect of vegetation on erosion is represented by the cover-management factor for non-agricultural land ($C_{non\text{-}crop}$ factor). This study presents an optimized computational procedure for estimating and mapping $C_{non\text{-}crop}$ within the Google Earth Engine (GEE) cloud-computing platform using multi-source satellite and climatological datasets.

Fractional vegetation cover (FVC) was first derived from NDVI, and land-use types were classified into forests, grasslands and shrublands, and other categories based on the MOD12Q1 product. Distinct calculation approaches were applied for each land-use class. For deciduous forests, the pixel-trisection model was used to improve the estimation of understory cover, with winter non-photosynthetic vegetation (fNPV) serving as an indicator of understory conditions. For grasslands and shrublands, an empirical formulation was adopted, while other land-use categories were assigned parameter values based on expert knowledge. To improve rainfall-erosivity estimation, three daily precipitation datasets (CHIRPS, ERA5, and PERSIANN-CDR) were evaluated against national meteorological station observations, and rainfall erosivity was calculated for 24 half-month periods.

The $C_{non\text{-}crop}$ factor was then estimated by integrating rainfall erosivity, vegetation cover, and land-use information. Results demonstrate that combining high-resolution Sentinel-2 imagery with 10-m land-use data substantially enhances the accuracy and spatial detail of $C_{non\text{-}crop}$ estimates, enabling a transition from regional-scale to localized assessments. The computational framework developed in this study provides an efficient, scalable approach for soil-erosion monitoring and mapping across diverse river basins and regions, offering valuable support for precision soil-conservation planning and ecological management.

**Keywords:** Soil Erosion; Cover-Management Factor; Google Earth Engine; Soil Loss Ratio; Spectral Mixture Analysis

**Acknowledgments**

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# Temporal Dynamics and Mechanism Evolution of Biochar in Regulating Erosion Processes in China's Loess Plateau

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## ABSTRACT

Biochar, as a soil amendment, has been proposed as a promising strategy to mitigate soil erosion. However, long-term effects of biochar application on soil erosion process included rill erosion and interrill erosion remain poorly understood. This study investigated the long-term dynamics of soil erosion in response to biochar amendment under natural rainfall with five slope gradients (2°, 5°, 10°, 15°, and 22°) and six biochar application rates (0, 1%, 2.5%, 4%, 5.5%, and 7%) from 2017 to 2022. The results showed that biochar exhibits a notable temporal effect and mechanistic evolution in regulating soil erosion on the loess slopes. In terms ofrill erosion, during the initial application period (within 3 years), biochar application at 1%~4% reduced rill detachment capacity and erodibility by approximately 35% and 39%, respectively, whereas more than 4% biochar conversely promoted rill erosion.

After 3 years, all biochar application rates shifted to an inhibitory effect, with reductions exceeding 50%, and the reduction increased proportionally with the biochar application rate. This is attributed to the long-term improvement of soil aggregate structure through enhanced organic carbon under biochar influence. The study pioneered the development of a predictive equation for rill erosion parameters based on the soil physicochemical properties under biochar application. Regarding interrill erosion, biochar reduced runoff within the first 3 years but increased it afterward, while the inhibitory effect on erosion caused by biochar persisted for 5 years before turning promotional. At the slope scale, biochar consistently reduced runoff by 28% and soil erosion by 62% across all periods, with effectiveness positively correlated with the application rate. Ultimately, the study reveals that environmental factors such as rainfall and slope gradient exert a more dominant influence on soil erosion processes compared to biochar application rate and duration. Fundamentally, the enhancement of soil quality induced by biochar serves as the key driver regulating soil erosion process. These findings indicate that biochar can serve as an effective short-term soil conservation measure, but its efficacy is highly dependent on application rate, duration since application, rainfall type, and slope gradient.

**Keywords:** Biochar; Interrill and rill erosion; Modeling; Soil quality; Loess Plateau

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# Tracing soil redistribution rates following deforestation in Northern Hardwood Forests using $^{239+240}$Pu isotopes

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**ABSTRACT**

Accelerated soil erosion and deposition pose major threats to soil health and ecosystem services in forested landscapes. Clear-cutting, particularly whole-tree harvesting (WTH), in which the stem and crown are removed from the site, intensifies erosion processes. At the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, US, WTH was conducted in Watershed 5 between 1983 and 1985, and several studies have examined its ecological impacts; however, no study has evaluated its effect on soil redistribution. Here, we aimed to 1) quantify erosion and deposition rates along slopes following WTH using $^{239+240}$Pu, 2) evaluate soil morphological changes nearly 40 years after harvesting, and 3) test the suitability of $^{239+240}$Pu as a tracer in acidic sandy soils. The results revealed that WTH increased soil redistribution: mid-backslope soils showed erosion (−6.8 ± 3.33 t/ha/y), toeslope soils showed deposition (2.06 ± 2.56 t/ha/y), and upslope soils displayed values near zero. Our findings also indicate that a portion of the eroded material was exported out of the watershed, representing a direct pathway for soil carbon loss. Thinner organic horizons were the only remaining morphological sign of disturbance, indicating incomplete forest-floor recovery. $^{239+240}$Pu depth profiles showed strong near-surface retention with only limited lateral subsurface migration, confirming the suitability of $^{239+240}$Pu for tracing erosion processes in northern hardwood soils. These findings evidenced that WTH leaves a long-term geomorphic imprint and that soil redistribution play a key role on soil carbon dynamics, highlighting the need to consider erosion processes for sustainable forest practices, soil management, and carbon storage.

**Acknowledgments**

HBEF is located on the unceded land of the Wabanaki people. The site is maintained and operated by the USDA Forest Service, Northern Research Station, PA, USA. We thank Liz Kreitinger (Cornell University) and Lindsey Rustad (USDA Forest Service) for their support during study site selection. We also thank Amey Bailey for providing historical data and discussions of the results, and Jennifer Bower (University of Vermont) for field support. We are grateful to Rebecca Minor, Alana Margerum, Meg O'Brien, Henry King, Luke Sedor Protti, Evan Saltman, and Philip Dostie (Bates College) for their support during fieldwork and laboratory analyses. We also thank Jim Kaste (William and Mary University) and Joshua Landis (Dartmouth College) for discussions related to data analyses. We also thank William Ketterer (Northern Arizona University) for support during laboratory work. Financial support was provided by the Geological Society of America Stephen G. Pollock Undergraduate Research Grant, and the Bates Bouley-Creasy Fund for Eli Gundersen, and by the Bates Faculty Development Fund for Raquel Portes.

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# A Novel High-Resolution DEM Synthesis Method for Terraced Watersheds in the Loess Plateau

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## ABSTRACT

**Background:** Terraces enhance soil conservation ability by modifying micro-topography. Insufficient understanding of the topographic characteristics of terraced watersheds may significantly compromise the accuracy of soil erosion assessments. Digital Elevation Model (DEM) products generated through conventional methods are often constrained by coarse spatial resolution, which limits their capacity to accurately characterize the fine-scale micro-topography of terraced landscapes. Although DEMs derived from emerging Unmanned Aerial Vehicle (UAV) photogrammetry provide enhanced spatial resolution and can effectively capture structural characteristics of terraces, they remain susceptible to elevation biases in densely vegetated regions—particularly in shrub-dominated areas—due to interference from canopy height.

**Methods and Results:** To overcome these limitations, this study selects the Liudaogou Watershed in northern Shaanxi, Loess Plateau, as a representative case study area and proposes a novel method for generating high-resolution DEM specifically tailored to terraced watersheds (technical procedure illustrated in Fig. 1). The proposed approach integrates the complementary advantages of Gaofen-7 satellite-derived DEM and UAV-acquired DEM collected during fallow periods through an adaptive local filtering approach, thereby producing an enhanced DEM with superior spatial fidelity. Comparative evaluation against Gaofen-7-based DEM and UAV-based DEM, as well as field validation data demonstrates that the resulting DEM not only preserves critical structural elements and subtle local terrain variations characteristic of terraces but also significantly reduces vegetation-induced elevation biases, thereby improving overall accuracy and reliability.

**Conclusion:** The proposed method effectively captures the micro-topography of terraced watersheds, enabling more accurate assessment of soil erosion in the Loess Plateau.

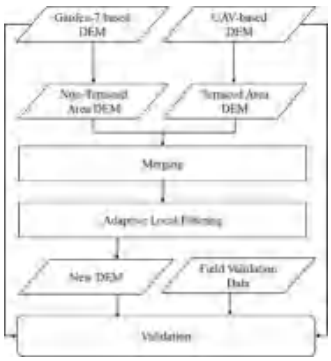



Fig. 1 Technical procedure.

**Keywords:** Terrace; High-Resolution DEM; UAV; Gaofen-7; Soil and Water Conservation.

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# Effects of crop type on the soil anti-scourability index of sloping farmland in the black soil region of northeast China

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**ABSTRACT**

The loss of soil and water on sloping farmland in the black soil region of northeast China is particularly severe and requires urgent attention. Changes in root characteristics and soil properties induced by different crop types considerably affect soil erosion. The soil anti-scourability index is a key parameter for evaluating soil erosion. However, the effects of crop type on the soil anti-scourability index regarding sloping farmland are not clear. Therefore, this study was conducted to quantify root characteristic effects of alfalfa, soybean, and maize on soil properties at different sampling stages, and to further identify factors influencing the soil anti-scourability index. Specifically, the soil anti-scourability index of alfalfa was significantly higher compared to soybean and maize. Compared with maize, the alfalfa treatment increased the soil anti-scourability index by 139.0% – 349.8%, while the soybean treatment increased the soil anti-scourability index by 19.9% – 37.5%. Structural equation modelling indicated that root characteristics influenced the agglomeration of soil aggregates, which increased both soil aggregate stability and macroaggregate ($WSA_{>0.25}$) abundance, thus ultimately increasing the soil anti-scourability index. Planting alfalfa is a practical and effective method for controlling soil erosion. The research results provide a practical application for improving soil erosion on sloping farmland and adjusting crop type.

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# Effects of Green Manure Incorporation and Tillage Practices on Soil Carbon Fractions and Soil and Water Losses in Sloping Red Soils

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## ABSTRACT

***Aims:***Green manure cultivation and tillage management are widely recognized as effective agronomic strategies to reduce soil use intensity, enhance productivity in multiple cropping systems, and mitigate soil erosion. However, under sloping farmland conditions, the combined effects of green manure incorporation and different tillage practices on soil physical structure and the stability of soil organic carbon (SOC) fractions remain poorly understood. This study aimed to systematically evaluate the interactive effects of green manure and tillage practices on soil properties, SOC fraction dynamics, and soil and water conservation in sloping red soils.

***Methods:***A field experiment was conducted in a sloping farmland double-cropping system with three treatments: green manure–maize under reduced tillage, green manure–maize under conventional tillage, and winter fallow–maize under conventional tillage. The effects of green manure combined with different tillage practices on soil physicochemical properties, SOC fractions, microbial biomass and enzyme activities, soil erosion, runoff-induced carbon loss, and maize yield were comprehensively assessed.

***Results:***(1) Compared with winter fallow–maize under conventional tillage, the integration of green manure with tillage significantly improved soil physical structure and nutrient status in sloping croplands, as indicated by a reduction in soil bulk density by 3.20–5.68% and an increase in SOC content by 2.95–11.57%. Among the treatments, the green manure–maize reduced tillage system exhibited more pronounced overall effects on improving soil structure and promoting carbon accumulation.(2) Improvements in soil structure and SOC status significantly enhanced soil and water conservation functions in sloping croplands. Green manure combined with tillage markedly reduced soil erosion intensity and runoff-mediated carbon losses, with runoff losses of total carbon, inorganic carbon, and dissolved organic carbon decreasing by 30.87–38.84%, 36.44–51.46%, and 33.98–51.70%, respectively. These erosion control and carbon retention effects were more evident under reduced tillage conditions.(3) Green manure rotation significantly increased maize yield by 11.54–14.57%, and yield was positively correlated with SOC and its labile fractions ($P < 0.05$), indicating that SOC, particularly the labile carbon pool, serves as a key regulator linking farmland management practices, soil and water conservation, and crop productivity.

***Conclusions:***Green manure incorporation increases organic matter and nutrient inputs and promotes crop growth, thereby improving soil physical structure and microbial activity. These changes enhance microbially mediated carbon transformation and stabilization processes, ultimately reducing the risk of soil and carbon losses through runoff and erosion. Overall, the integration of green manure with reduced tillage represents an effective management strategy that simultaneously improves crop yield and soil and water conservation, providing a sound theoretical basis and technical support for soil conservation practices in sloping farmlands of central Yunnan, China.

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# A Methodological Framework for Large-Scale Gully Erosion Assessment: Insights from Contrasting Landscapes of China

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**ABSTRACT**

Gully erosion is an important yet often insufficiently represented component of global soil erosion mapping, playing a key role in land degradation and sediment production in many agricultural and semi-arid regions. Despite major advances in high-resolution remote sensing, large-scale gully erosion assessment remains less developed than hillslope-scale studies, mainly due to methodological inconsistency and limited cross-regional comparability. In this study, we present a systematic framework for large-scale gully erosion assessment and examine its applicability using two geomorphologically contrasting regions in China: the Northeast Black Soil Region and the Loess Plateau.

Using sub-meter satellite imagery, Unmanned Aerial Vehicle (UAV) photogrammetry, and extensive field surveys, we compiled a multi-scale gully inventory and assessed its suitability for large-scale mapping. Clear regional differences in gully development were identified. Gully density in the Loess Plateau (4.08 $km \cdot km^{-2}$) is considerably higher than that in the Black Soil Region (1.12 $km \cdot km^{-2}$), while the latter has shown rapid gully expansion over the past 15 years. Gully occurrence is primarily controlled by topographic factors, especially slope gradient and slope length, together with precipitation, and these controls exhibit nonlinear threshold behavior and strong spatial heterogeneity across regions.Comparison with UAV and field observations shows that sub-meter satellite imagery provides a reliable basis for large-scale gully mapping, with gully length identification errors below 6%. On this basis, we developed a predictive framework that combines unequal probability stratified sampling with machine learning to estimate regional gully density, yielding acceptable performance at the large scale (Nash–Sutcliffe Efficiency = 0.6).

The results demonstrate that combining appropriate sampling strategies with data-driven models is essential for advancing large-scale gully erosion mapping within global soil erosion assessments. Future work should focus on dynamic gully monitoring using high-temporal-resolution remote sensing, the development of transferable artificial intelligence methods for gully detection based on high-resolution imagery, and improved approaches for estimating gully depth. The proposed framework offers a practical methodological References for incorporating gully erosion into large-scale soil loss assessments and soil and water conservation planning.

**Keywords:** soil erosion, gully, regional scale, high resolution remote sensing

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# Regional-Scale Variability and Environmental Drivers of Soil Erodibility factor (K) in the NW Italian Alps

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**ABSTRACT**

Predicting soil erodibility in mountain landscapes remains difficult because steep terrain, heterogeneous soils, and strong environmental gradients generate marked spatial variability. This is the case in the Aosta Valley (NW Italian Alps), an alpine region known for its pedological and ecological complexity. In this study, we focused on the topsoil erodibility factor (K) of the USLE, starting from the assumption that—under relatively uniform texture typical of this area—soil organic matter (SOM) would represent the main source of variability in K. We computed K using both USLE (Wischmeier and Smith, 1978) and EPIC (Williams et al., 1983) equations and, for illustrative purposes we extended SOM values beyond the traditional limit of the USLE nomograph to evaluate its behaviour in highly organic alpine soils. To map K across the region, we applied a Digital Soil Mapping (DSM) workflow based on machine-learning models, and we examined field, laboratory data and environmental covariates to better understand how K relates to soil properties. We also derived USLE-based erosion estimates for selected profiles to indirectly evaluate whether the K calculations are consistent with observed soil behaviour. Our results indicate that: (i) the USLE K equation better captures mountain complexity; (ii) SOM significantly reduces K, with stone cover exerting additional influence; (iii) the model identified key regional drivers of K (carbon stock, elevation, pH), producing consistent spatial maps at 40 m resolution; and (iv) K values vary across soil horizons, humus systems, land uses, and soil types. Estimates of erosional denudation further highlight the central importance of SOM in enhancing the resistance of mountain soils. Although part of our modeling approach extends beyond the validated SOM range, we hope this study provides a perspective highlighting that mountain soils may not be inherently as vulnerable as conventionally estimated by standard models, emphasizing the importance of properly accounting for SOM when assessing erodibility in alpine environments.

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# Influence of grazing on soil structure of the Patagonian wetlands meadows (Vegas)

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## ABSTRACT

The Vegas meadows of the sub-Antarctic steppe of Patagonia constitute the main forage for livestock production; the main economic input for Region of Magallanes. This causes overgrazing with a subsequent meadow and soil degradation. Additionally, owing to their high humidity, they must be drained to assess the correct air fraction in the pore system. This management in general causes irreversible settlement, high shrinkage and low swelling capacity as they present a great amount of organic carbon (15-30%). These negative consequences require the development of water conservation practices, such as drainage water management (controlled drainage), that allow the control of the phreatic level, reducing drainage intensity and rates during winter months. This allows water conservation, but also can prevent soil degradation, since appropriate water content allows a more stable soil structure, capable of supporting animal loads without significant negative effects of animal trampling. However, there are very few investigations related to the hydraulic and physical behavior of these ecosystems under drainage and grazing. Therefore, this study aims to determine the influence of drainage on the properties related to the soil structure under Patagonian wetlands meadow (Vegas). To determine this, in a split-split-plot design 3 treatments were established: i) controlled drainage, ii) free drainage, iii) control or non-drained, with two different stocking rate treatments using ewes 1) 1 OE $ha^{-1}$ $year^{-1}$ and 2) 4 EO $ha^{-1}$ $year^{-1}$. Animal entrance:
availability of dry matter between 2,100 and 2,300 kg DM $ha^{-1}$, and the grazing period: one month for all treatments. The CD considers a phreatic level depth between 30 - 50 cm and FD: 100 cm from the soil surface. Before and after the grazing events, undisturbed soil samples were collected from soil surface (0-10 cm). From the samples, the: pore size distribution (PSD) together with air conductivity, precompression stress (Pc), were determined for both animal loads and drainage treatments, were determined in undisturbed soil samples taken from first 10 cm. Generally, both variables influence the investigated properties.
More intensive grazing leads to greater soil degradation, reflected in reduced precompression stress and airflow. Pore size distribution demonstrates its positive distribution from an agricultural perspective, as it increases the soil's water retention capacity. However, if we consider the role of wetlands as water reservoirs, this capacity decreases due to the loss of macropores. For the Patagonian wetlands, these are the first results associated to physical compartment of these ecosystems and can constitute the basis for grazing management, allowing for adjustment of stocking rates to soil moisture (regulated by drainage).

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# Spatial Distribution and Erosional Significance of Hollows in Agricultural Landscapes of the European Russia

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**ABSTRACT**

Hollows (linear depressions belonging to the upper reaches of fluvial network) are among the most common landforms on arable lands in Russia. They concentrate surface runoff on the slopes that promote to soil erosion rate increasing and formation of ephemeral gullies. Also some sections of their bottoms often serve as sediment sink.

Hollows are clearly visible on a ultra-high-resolution satellite images (less than 1 m) due to a darker phototone of their bottoms associated with relatively high water saturation of the surface deposits. Hollows have either a linear or a dendritic pattern in plan view.

The most hollows of central and southern European Russia are Pleistocene relicts (Eremenko & Panin, 2010). Previous studies have identified spatial variations in their patterns across the East European Plain and described their geology. Local assessments have shown an order-of-magnitude increase in soil erosion rates on arable slopes with a network of hollows (Desmet & Govers, 1997; Zhidkin et al., 2025).

In this study, we mapped the hollow network within 18 municipal districts of European Russia with high proportion of cultivated lands. The studied areas differ in their predominant soil types and topography. Spatial variability in hollow density on arable land was assessed by calculating a density metric (the ratio of total thalweg length of hollows to the area of agricultural fields). Several types of dendritic hollow networks were identified based on the results of satellite imagery interpretation. Quantitative assessment showed a clear differentiation: the average hollow density on arable land was more than twice as high in upland areas (1.6 $km^{-1}$, range 0.23–4.58) than in lowlands (0.76 $km^{-1}$, range 0.27–1.25). The completed assessments will allow us to estimate their contribution to the overall soil fertility loss.

**Acknowledgments**

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# Influence of Soil Cover Properties on Shallow Landslides: insights from a Pilot Basin in Southern Italy

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## ABSTRACT

Properties of soil cover play a crucial role in controlling natural processes that actively shape and modify landscapes. The project "SOIL SHADES" focused on a multi-scale and multi-analytical approach to enhance understanding of soil characteristics that control the occurrence of shallow landslides by integrating geomorphological, geophysical, and pedological analyses. The research has been carried out in a pilot catchment (Turbolo Stream) of the Calabria region (southern Italy) due to its representativeness of several Mediterranean environments. The basin has an extension of approximately 30 km$^2$ and exhibits an important lithological, geomorphological and pedological variability. Six locations struck by shallow landslides were selected across the catchment because of distinctive parent material and geomorphological features: i) soils developed from Palaeozoic metamorphic rocks on high relief and steep slopes under beech forest, ii) soils from Miocene to Pleistocene clay deposits on hilly morphology, iii) soils from Holocene sand and conglomerates of alluvial terraces in arable lands. On slopes carved into the different lithological types and affected by shallow earth slides (roto-translational movement), multitemporal geomorphological analyses using satellite images, digital elevation models (DEMs) and field surveys allowed detailed mapping of the landslide bodies and related morphological features. Geophysical prospections, using 2D-electrical resistivity tomography (ERT) and electro-magnetic induction (EMI) surveys, were combined to map the soil spatial variability, to provide a comprehensive understanding of geometric features of the landslides, and to identify the depth of possible shallow sliding surfaces, due to the effectiveness of both techniques in the detection of geological and pedological discontinuities.

Six representative soil profiles were analysed across the Turbolo catchment, in the detachment crowns of the main landslides. Soils ranged from highly developed with clay-enriched subsoil (Luvisols) on sand and conglomerate deposits, to vitric (Andosols) on metamorphic rocks, and vertic (Cambisols) soil properties on clay deposits. Consistently, the lowest values of the $Fe_{ox}/Fe_{dith}$ ratio (from 0.3 to 0.11) ($_{ox}$ = oxalate extractable; $_{dith}$ = Na dithionite-citrate-bicarbonate extractable) were measured for the Luvisols, while the highest (0.12 to 0.26) for the Andosols. However, the $Fe_{ox}/Fe_{dith}$ ratio varied along the depth, as well as the Ti/Zr ratio, the clay content, the coarse fragments and the soil organic matter, marking discontinuities potentially acting as sliding surfaces.

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# Effects of irrigation timing on early growth of Haloxylon ammodendron seedlings in southern Tajikistan

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**ABSTRACT**

*Haloxylon ammodendron* is a key afforestation species widely used in arid and desert regions due to its critical role in desert land restoration and erosion control. A five-year field study (2021–2025) was conducted in the desert zone of southern Tajikistan, Shahrituz district (300–350 above sea level; annual precipitation: 166mm; annual temperature: 17.2 °C) to assess the long-term effects of irrigation initiation timing on growth following irrigation cessation. 1–year–old *H. ammodendron* seedlings were established at a spacing of 6 m × 2 m (833 seedlings $ha^{-1}$). Irrigation was applied only during the first year after planting at a rate of 6–8 L per seedling every 35–40 days and the two irrigation regimes—winter and spring irrigation—were compared. In 2025 after 4–5 years without irrigation, winter-irrigated seedlings exhibited greater height (30–180 cm) and root collar diameter (10–41 mm) compared with spring-irrigated seedlings (24–155 cm and 10–35 mm, respectively). Winter irrigation enhances soil moisture infiltration and reduces evaporative losses, enabling effective root development before the onset of the hot season. In contrast, spring irrigation suffers from high evaporation rates, particularly in sandy soils, limiting water availability for seedling establishment. These findings provide long-term field evidence that winter irrigation significantly enhances early root establishment and improves seedling growth, representing a more effective strategy for desert afforestation under arid conditions.

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# Practical-measures investigation to achieve global soil erosion map by using sampling method

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**ABSTRACT**

As the 1st threat to the planet's soil, erosion significantly degrades the soil characteristics, and therefore it is the greatest challenge for sustainable agricultural management. Over the past 30 years, the World is suffering from a serious process of land degradation as a result of global climate change and the increasingly acute conflicts among population, resources and the environment. In order to reverse this trend towards land degradation, many regions and countries have carried out sustained and painstaking initiatives for soil and water conservation, whose results has been monitored using different methodologies. It is urgent to adopt state of the art technologies including the latest earth observation techniques to evaluate global soil erosion status and soil conservation benefit in a standardized way. Accurately achieving the status of global soil erosion and the distribution and types of soil/water conservation measures, will help to illustrate the difference in effectiveness of soil/water conservation practices, improve current technologies, promote soil/water conservation measures, eliminate interregional imbalances and promote the United Nations' Sustainable Development Goals using solid science.

Current methods for conducting national and regional-scale soil erosion evaluations include the following three main categories, depending on the method of data acquisition and analysis: sampling survey method, remote sensing survey method, and grid calculation methods. We briefly describe the data acquisition process, analysis method, and development history of the three methods, and compare their advantage and disadvantage from the perspective of reflecting the real soil erosion status on the ground and the effectiveness of soil/water conservation measures. From the perspectives of the diversity of soil and water conservation measures, the positive effects of controlling erosion processes, and the economy, flexibility and timeliness of global mapping, we believe that planning and deploying reasonable stratified-systematic sampling units globally, and adopting high-accuracy remote sensing imagery for extracting and quantitatively expressing soil/water conservation measures, are the prerequisites and foundation for global soil erosion assessment and mapping with guaranteed accuracy.
**Keywords:** Sampling method; Soil conservation measures; Global soil erosion map; Land degradation; Sustainable development

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# Weakened role of check dams in reducing erosion-induced soil organic carbon transport in the Middle Yellow River Basin due to vegetation restoration

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**ABSTRACT**

Soil erosion redistributes soils and soil organic carbon (SOC) across landscapes. Vegetation restoration and gully-control engineering, particularly check dams, play crucial roles in mitigating erosion and adapting to climate change. Yet, owing to the efficient representations of cascading dams, the large-scale, spatiotemporal impacts of check dams on eroded SOC yield remain unclear, as do the evolving contributions of rainfall, vegetation, and dams. Using the latest check dams dataset and an improved erosion assessment model, we quantified the spatial and temporal dynamics of eroded SOC yield in the Middle Yellow River Basin from 1970 to 2020. The results show that check dams cumulatively trapped 20.80 TgC of SOC, accounting for 11.07% of the total loss. Within dam-controlled watershed, the relative contribution of check dams to reducing eroded SOC yield decreased from 99.10% in the early restoration period to 30.18% in the later period, while vegetation restoration became the dominant controlling factor in recent decades (75.78%). This study establishes a globally applicable framework for assessing eroded SOC yield, advances the understanding of the synergistic effects between vegetation restoration and check dams, and provides scientific guidance for sustainable erosion control and dam management.

# The efficacy of hedgerow-grass ditch systems in controlling N and P losses in citrus orchards under variable natural rainfall events

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**ABSTRACT**

The hedgerow-grass ditch systems (HGDS) is a recognized soil erosion control measure on slopes. However, its efficacy in reducing nitrogen (N) and phosphorus (P) losses across varying rainfall amounts (RM) and vegetation cover remains unclear. In this 3-year field study (2022–2024) in a purple soil citrus orchard, we evaluated six treatments, namely clean-tilled citrus orchard control (CK), *Trifolium repens* L. HGDS in citrus orchard (T1), *Chrysopogon zizanioides* (L.) *Roberty* HGDS in citrus orchard (T2), agroforestry citrus orchard (citrus intercropping with vegetables) (T3), *Trifolium repens* L. HGDS in agroforestry citrus orchard (T4), *Chrysopogon zizanioides* (L.) *Roberty* HGDS in agroforestry citrus orchard (T5), across 26 erosive events spanning four RM categories (moderate rain, heavy rain, rainstorm, and large rainstorm). Runoff depth (RD), sediment yield (SY), and the concentrations and losses of total, dissolved, and particulate N and P (TN, DN, PN, TP, TP, PP) were measured. Surface runoff was initiated at 24-h rainfall above 20 mm. Compared to CK, T1–T5 significantly reduced RD (26–71%), SY (62–89%), TN loss (57–86%), and TP loss (58–81%). Treatment DN comprised 57–75% of TN loss, whilst DP accounted for 43–50% of TP loss. As RM increased from moderate, heavy, rainstorm to large rainstorm, runoff depth rose by 29.3%, 71%, and 75%, respectively; sediment yield increased by 5.4, 5.3, and 22.5 times; TN loss grew by 3.2, 3.8, and 8.8 times; and TP loss was 3.9, 5.4, and 4.8 times higher, respectively. Runoff depth and sediment yield were significantly positively correlated with TN and TP loss, but the magnitude of these responses varies significantly across different treatments, with strong positive correlations observed in CK. These responses were significantly attenuated under HGDS treatments. Based on the results, the effectiveness of HGDS in mitigating nutrient losses in sloping agroforestry systems, supporting its use in sustainable hillslope management.

**Keywords:** Hedgerow; grass ditch; N and P loss; citrus orchards; sloping land; soil and water conservation measures

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# Soil and Water Conservation Planning by Estimating Complex Soil Properties from Easily Measurable Soil Properties

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**ABSTRACT**

Soil erosion by water is one of the most critical environmental concerns and a leading cause of land degradation. The hilly Shiwalik-*Kandi* region of Punjab, India experiences severe soil erosion affecting productivity and soil quality. Understanding soil properties such as aggregate stability and erodibility is essential for soil and water conservation planning. However, direct measurement of these parameters is difficult, costly and time-consuming. Hence the present study explores empirical, statistical and machine learning (ML) approaches for estimating complex soil properties from easily measurable parameters.

The study was conducted in the *Kandi* region of Punjab, India under different land uses – forest, grassland and cultivated lands. Three datasets including soil texture, bulk density, pH, EC, organic carbon, Fe, $CaCO_3$, and cation exchange capacity were used. For each data set, 70% of the data was used for training and 30% for testing. Empirical pedo-transfer functions (PTFs), generalized linear models (GLMs), and artificial neural networks (ANNs) were applied using BigML software to estimate mean weight diameter (MWD), water-stable aggregates (WSA), and soil erodibility (K-factor).

Results indicated significant variations in basic soil properties under different land uses. Organic carbon and aggregate stability were higher in forest and grassland soils. For data sets with fewer variables, GLM provided better results, while ANN outperformed for larger, complex data sets. ANN models captured nonlinear interactions effectively and provided superior prediction accuracy for MWD, WSA and K, confirming their potential for large-scale applications.

The study concludes that machine learning, particularly ANN, offers an efficient, data-driven, and scalable alternative for estimating complex soil properties. Combining traditional, statistical and ML approaches enhance prediction accuracy and supports evidence-based soil and water conservation planning. The integration of artificial intelligence with soil data and remote sensing can revolutionize digital soil mapping and sustainable land management in fragile ecosystems like the *Kandi* region.

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# Simulation of Wind Erosion under the Influence of Topography in a Temperate Grassland Landscape

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**ABSTRACT**

Wind highly varies temporally and spatially, resulting in the obvious variation of wind erosion. Such variation has less been considered at the landscape scale. In landscapes with complex topography, wind field is strongly influenced by both terrain and vegetation. This study simulated wind erosion in a temperate grassland landscape by integrating the revised wind erosion equation (RWEQ) and computational fluid dynamics (CFD). Wind field over the landscape was modelled by CFD, which considered both the effects of topography and vegetation. Wind erosion rates were compared with the results based on the fallout radionuclide method, which showed satisfied agreement. The findings demonstrate that both topography and vegetation have vital impacts on wind erosion, and the integration of RWEQ and CFD can effectively improve the simulation of wind erosion at the landscape scale.

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# Effects of grass structure on wind erosion using a wind tunnel simulation

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**ABSTRACT**

Wind erosion is a major environmental problem contributing to land degradation in arid and semi-arid grassland ecosystems. However, the impacts of vegetation structure on wind erosion remain poorly understood. This study quantified the effects of grass roots, flat residue coverage (90%, 60%, 40%, 25%, and 15%), standing residue and living grass height (30 cm, 15 cm, 5 cm) and coverage (90%, 60%, 40%, 25%, and 15%) on wind erosion using wind-tunnel experiments at different wind speeds (9 and 12 ms-1). Results showed that living grass and dead residue with the same height and coverage has similar wind erosion control effects. The soil loss decreased 16.7%-70.7% grass and residue coverage increased from 15% to 90% at 9 m/s, while it decreased 22.4%-66.5% at 12 m/s. Additionally, the wind erosion rates decreased 46.7%-90.9% with grass and residue heights increased from 3 cm to 30 cm at 9 m/s, while decreased by 40.9%-90.9% at 12 m/s. When residue or grass height was ≥15 cm and cover exceeded 60%, soil loss was reduced by more than 90%. However, grass roots alone without canopy showed weak erosion control effects. The wind erosion rates were 9.5 and 16.1 g $m^{-2}$ $min^{-1}$ with root density varied from 16.7 $gm^{-2}$ to 4.58 $gm^{-2}$, which were only 6.8 and 0.3 g $m^{-2}$ $min^{-1}$ lower compared to the bare-ground values at 9 ms-1. When the coverage of flat residue increased from 15% to 90%, the soil loss by wind decreased 30%–40% compared to the condition having roots only. Further analysis indicated that residue or living grass coverage had the largest contribution for erosion control (contributed 70%-80%) when residue or grass height was >15 cm, while the flat residue coverage had a more significant impact on wind erosion control compared to roots that were very limited in direct wind erosion control. These findings provide quantitative thresholds for vegetation-based wind erosion control and support improvements in wind erosion modelling and grassland management strategies.

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# From Aerosols to Soils: A Novel Pedological Framework for Identifying Aeolian Dust Hotspots in Dried Saline Lakebeds

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**ABSTRACT**

The issue of fast desiccation ofinland hypersaline lakes is one of the most essential, though not elaborated, issues in current soil science. Besides hydrological degradation, lake desiccation is a significant factor that causes alterations in soil physical properties, lake surface crust, as well as soil susceptibility to wind erosion, meaning that soil systems of such lakes change drastically. The problem of aeolian dust emission is considered from a soil perspective. Based on the representative hypersaline lake, Urmia, this study initiates a new conceptual model with "Coldspots," "Hotspots," and "Hottestspots" of dust emissions by employing the joint properties of aerosol optical depth value, frequency, and variability from long-term MAIAC/MODIS satellite observations. Contrary to conventional hotspot mapping, which neither distinguishes actual dust emissions from transported dust clouds nor considers them individually, this model specifically identifies local dust-emitting surfaces in direct connection with soil erodibility classes.

The findings indicate a close relationship between the area development of Hotspots and Hottestspots, and major soil characteristics within the desiccated lake. The finer texture of clay-silt deposition and puffic crusts is prevalent in the southern and central parts, and these are less susceptible to wind erosion, whereas salt-affected and salt- clay crusts in the northern parts are found to be less resistant despite similarity in wind energy. The findings clearly indicate that in desiccated saline environments, wind erosion is not a function of wind energy but is dependent on soil characteristics.

From a pedological perspective, arid hypersaline lake beds are a transitional soil type that lies between the zones of lacustrine soils, saline-sodic soils, and dynamic aeolian features. The soil type is prone to extreme aggregation stability transformations, threshold friction velocity, and surface stability properties affected by climate-induced stress and improper water management. The integration of aerosol algorithms with soil processes makes the proposed work a transferable methodological framework that focuses on soil.

This proposed framework has immediate relevance for soil conservation, desertification studies, and measures for combating dust in arid and semi-arid areas facing intense lake shrinkage. This relevance can now be extended to China, Central Asia, and the drylands of the world. This presentation at the 2026 Meeting of the Chinese Soil Science Congress can thus add a new dimension to the studies of aeolian processes using soil process insights. This can lay the groundwork for international collaboration for soil system management in arid conditions due to climate changes.

**Keywords:** Aeolian processes; Soil degradation; Dust storms; Saline-lake environments; Wind erosion.

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# Modeling runoff and soil erosion amounts affected by slope gradient and length in black soil slope farmland of Northeast China based on APSIM

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**ABSTRACT**

The black soil region had more ridge cultivation slope farmland, which results in a serious threat of soil erosion caused by water as well as corn yield decreasing. Conservation tillage was beneficial to agriculture production, whereas few study investigated the soil erosion and runoff affected by slope gradient and length under conservation tillage used for Agricultural Production Systems Simulator (APSIM) simulation. In this study, APSIM was calibrated and validated by soil characteristics and corn yield under rotary tillage (RT), no-tillage without straw mulching (NT), no-tillage with straw mulching (NT-SM) and strip tillage with straw mulching in wide rows (ST-SM) treatments, which were used to investigate the regularity of soil erosion and runoff under slope gradient 3°, 6°, 9°, 12°, 15°, 18°, 21°, 24° as well as length 50 m, 100 m, 250 m, 500 m, 750 m, 1000 m, 1250 m under long-term (1981-2023) meteorological data. The result showed APSIM greatly simulated soil erosion amounts, runoff depth and corn yield with normalized root mean square errors (NRMSE) of 48.30-93.25%, 37.41-77.55% and 5.98%, respectively. The simulated soil erosion amounts significantly increased with slope gradient and length, whereas simulated runoff depth increased with no significant difference. Tillage and climate significantly affected simulated soil erosion amounts (0.56 and 0.63, -0.88 and -0.92) and runoff depth (0.14 and 0.15, 0.50 and 0.56). Conservation tillage (NT-SM and ST-SM) significant decreased soil erosion amounts and runoff depth compare with rotary tillage, reduction rate progressively increased with slope length and gradient by more than 96% and 25%, respectively. However, reduction rate of simulated soil erosion amounts and runoff depth of NT treatment relative to rotary tillage progressively decreased with slope gradient by 16.62-15.30% and 14.23-12.89%, and significantly lower than NT-SM and ST-SM treatment. Corn yield was decreased under NT and NT-SM treatments by 3.16% and 7.02% compare with RT treatment, the highest corn yield was found at ST-SM treatment 11.40 t ha-1 (2.89%). In conclusion, APSIM was acceptably applied to simulate soil erosion and runoff in slope farmland, the effect of decreasing soil erosion and runoff of no-straw-mulching practice was insufficiently compared with straw mulching practice in slope farmland. NT-SM treatment was most effective in resisting soil erosion under slopes below 6° and 250 m, ST-SM treatment was more suitable for slopes above 9° and 500 m and increased corn yield.

# Hydrologic regime determines catchment-scale dissolved carbon export patterns

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**ABSTRACT**

Hydrologic regimes are affecting terrestrial carbon transformation, chemical weathering and lateral transport. However, its impacts on dissolved carbon export patterns remains elusive. In this study, we collected a 2-year high-frequency dissolved inorganic (DIC) and organic carbon (DOC) dataset, namely a wet year (Rainfall=1158 mm) and a dry year (Rainfall=603 mm). The results showed that drought led to a significant decrease in dissolved carbon concentration and discharge during the monitoring period. During non-storm periods, DIC and DOC shifted from dilution and chemostatic to enrichment patterns from wet to dry years, respectively. However, the export patterns were reversed during storm periods. DIC and DOC export patterns in wet year were dominated by dilution and chemostatic, respectively, while both patterns were dominated by dilution in dry year. Structural equation models revealed that the aridity index and temperature may affect dissolved carbon export patterns. We further classified storm events into three major types and conceptualized catchment-scale transport mechanisms for dissolved carbon. Dry-AMCs events result in DIC dilution and DOC chemostatic behavior, whereas Wet-AMCs events result in DIC chemostatic and DOC enrichment behavior due to increased hydrological connectivity. The third type corresponds to extreme events, where larger overland flow often results in DIC dilution but DOC enrichment behavior. These findings reveal the predominant role of drought in altering carbon lateral export by decreasing concentrations and fluxes and modifying export patterns.

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# Dynamics of Soil Carbon and Nitrogen in Check-Dam Sediments: Impacts of Burial Time and Decadal Exposure Following Dam Breaching

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**ABSTRACT**

Understanding the long-term fate of eroded carbon (C) and nitrogen (N) sequestered behind check dams is crucial for assessing their role in biogeochemical cycling within human-altered landscapes. We characterized the vertical distribution of C and N components, microbial metabolic parameters, and mineralization potentials along a 0-1058 cm sediment profile of a check dam on the Loess Plateau. Sediment burial time and historical sediment yield modulus were determined based on sedimentary couplets. The impact of dam breaching was assessed by comparing sediments exposed for a decade with adjacent buried layers. Soil organic carbon, total nitrogen, dissolved organic carbon, extracellular enzymatic activity, and the mineralization rate of carbon and nitrogen fluctuated with the deposition couplets of the clay/sand layer in the check dam. Soil organic carbon, total nitrogen, carbon nitrogen ratio, dissolved organic carbon, and inorganic nitrogen were higher in check dams than those of the slope in corresponding amounts of 59%, 40%, 18%, 22%, and 327%, respectively. Microbial biomass peaked during the severe erosion stage (1959–1961), while microbial carbon limitation was at its lowest. Microbial phosphorus limitation was lowered throughout the erosion reduction stage (1962–1998) and control stage (1999–2012). While the microbial carbon limitation decreased with the increase in sediment yield modulus, soil organic carbon content and total nitrogen content in the clay layer of the deposition couplets both greatly increase. With an increase in sediment yield modulus, the total nitrogen content of the sand layer increased firstly and then decreased. In comparison to the buried sediment, the exposed sediment had significantly higher soil dissolved organic carbon and inorganic nitrogen, higher soil microbial phosphorus limitation, and lower soil organic carbon mineralization rate, mineralization ratio, and soil metabolic entropy. In conclusion, soil carbon and nitrogen in check dams were more difficult to decompose than those on slopes, and microorganisms were preferred to assimilate carbon rather than release it and this trend increased as burial times increased and after a decade of exposure.

**Keywords:** Check dam; Deep soil; Dam-break; Carbon and Nitrogen mineralization; Microbial metabolic limitation

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# Field Evaluation of Vegetation with Contrasting Root Traits for Runoff and Soil Erosion Control on Sloping Agricultural Land

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**ABSTRACT**

Vegetation-based approaches are widely applied for runoff and soil erosion control on sloping agricultural land; however, their effectiveness is often evaluated using mean erosion rates without explicit consideration of rainfall regimes or plant root functional traits. This study presents a field evaluation of vegetation with contrasting root traits for runoff and soil erosion control on sloping agricultural land in a humid tropical environment. Root system architecture and mechanical properties of selected plant species were first characterised through controlled support experiments using rhizobox observations and root tensile-strength testing. Field runoff and erosion measurements were carried out on bounded runoff plots under natural rainfall conditions and categorised into wet and dry spells based on rainfall characteristics and antecedent soil moisture. Results showed that vegetation effects on runoff and soil erosion were strongly rainfall-regime dependent. During wet spells characterised by high rainfall intensity and near-saturated soils, deep-rooted vegetation with mechanically strong and vertically extensive root systems substantially reduced runoff coefficients and soil loss. In contrast, shallow-rooted or mat-forming vegetation increased runoff and soil loss relative to the control under saturated conditions, indicating limited infiltration and enhanced surface flow concentration. Vegetation with dense surface cover but limited anchorage provided moderate erosion reduction under wet spells. During dry spells, runoff and soil loss were generally low across treatments, and differences among vegetation types were markedly reduced, reflecting threshold-controlled runoff generation. Only vegetation that enhanced near-surface soil structure and infiltration showed distinct reductions in runoff and erosion under low rainfall intensity. The findings demonstrate that vegetation effectiveness for erosion control is conditional and process-dependent. Evaluation of vegetation-based soil conservation measures without consideration of the rainfall regime may lead to misleading conclusions. A trait-based approach that matches plant root functional traits to dominant erosion processes provides a more robust framework for designing vegetation-based soil and water conservation measures on sloping agricultural land in humid tropical environments.

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# Variability of hydraulic characteristics of sediment-laden rill flow under various slopes, water flows and sediment loads

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**ABSTRACT**

During soil erosion, sediment load of rill flow changes dynamically and may affect its hydraulic characteristics. However, current research on hydraulics of sediment-laden rill flow primarily uses river sand/artificial homogeneous materials as sediment, which significantly differ from natural soil, leaving a research gap on how soil quantity impacts rill flow hydraulics. This study uses natural soil in an indoor rill flume simulation experiment to explore how sediment load influences hydraulic characteristics of rill flow, including flow velocity ($V$), Darcy–Weisbach friction coefficient ($f$), Reynolds number ($R_e$), Froude number ($F_r$), and flow depth ($h$). Experiments were conducted under combinations of six different sediment loads, five flow discharges, and five slopes. The results indicated that $V$, $f$, $R_e$, $F_r$ were significantly influenced by sediment concentration. $V$ and $F_r$ show an upward trend as the sediment load increases, while $f$, $R_e$, and $h$ demonstrate a downward trend. The sediment load predominantly influences $V$, $f$, and $F_r$, accounting for contributions of 0.33, 0.49, and 0.39, respectively. The influence of slope gradient on $V$ and $F_r$ intensifies as the sediment load increases, while the impact of flow discharge on $V$, $f$, and $F_r$ diminishes. As flow discharge increases, the effect of sediment load diminishes on $V$ and $F_r$, and that of slope gradient strengthens. Two kinds of prediction equations were developed for estimating the hydraulic parameters of sediment-laden rill flow. The models demonstrate high $R^2$ values (0.74 to 0.98), suggesting strong performance of the prediction equations. These findings lay a foundation for the better development of a physical process-based rill erosion model. Given the differences in the properties of natural soils, which may impact hydraulic characteristics, it is a limitation of this study that it only focuses on a single soil type, and thus future research should explore the effect of sediment properties on hydraulic characteristics.

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# Effects of Crop Association on Soil Extracellular Enzyme Stoichiometry in Erosion-Prone Sloping Farmlands in the Rocky Mountainous Region of North China

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**ABSTRACT**

Soil extracellular enzymes—bioactive compounds produced by soil microorganisms, plants, and animals—play a central role in mediating material cycling and energy flow within grassland eco-systems. These enzymes decompose complex organic matter and respond dynamically to environmental perturbations. Their activities and stoichiometric ratios are widely recognized as reliable indicators of soil nutrient limitations. This study identified typical sloping farmland within the Grade I Water Source Protection Area of Taishizhuang Village, Taishitun Town, Miyun District, Beijing, China (117°6′42.08″E, 40°32′22.02″N) and applied in situ field monitoring and laboratory analyses to evaluate four crop association treatments that were based on ecological adaptability, functional complementarity, and economic value: T1 (*Medicago sativa* + *Buchloe dactyloides*), T2 (*Scutellaria baicalensis* + *B. dactyloides*), T3 (*Platycodon grandiflorus* + *Cynodon dactylon*), and CK (bare land control). The objective was to elucidate the effects of plant configuration on soil physicochemical properties, extracellular enzyme activities, and microbial nutrient limitation mechanisms. Key findings were, firstly, that crop association and its interaction with slope position influenced soil particle composition, moisture content, and chemical characteristics ($P < 0.001$), while slope position alone primarily affected clay content and water retention. T1 had the largest soil improvement effect ($P < 0.05$). Secondly, soil enzyme activities were positively correlated with total nitrogen, soil organic carbon (SOC), and soil water content, while sand content and $NO_3^-$–N showed negative correlations. These factors varied spatially by slope position ($P < 0.05$). Sand content was higher on the upper slope (74.8%) than on the lower slope (72.1%), while peak enzyme activity was driven by higher soil organic matter (8.33 g/kg) and clay content (8.8%) on the middle slope. Elevated $NH_4^+$–N levels on the lower slope (11.14 mg/kg) influenced enzyme activity in that zone. Phosphorus limitation was more pronounced than nitrogen limitation throughout the study area. Crop association influenced microbial nutrient limitations by modulating SOC and $NO_3^-$–N concentrations ($P < 0.05$). T1 and T2 notably increased microbial carbon limitation ($P < 0.05$), while T1 also produced lower phosphorus limitation across all slope positions ($P < 0.05$). Thus, the *M. sativa–B. dactyloides* crop association (T1) was most effective in enhancing soil quality and microbial metabolic function in erosion-prone sloping farmlands. These findings provide a foundation for designing crop associations aimed at soil and water conservation in rocky, mountainous regions of North China.

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# Influence of land use change and increased rainstorm on shallow landslide sediment connectivity in a small watershed of the Chinese Loess Plateau based on remote sensing

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**ABSTRACT**

Shallow landslide, a serious gravity erosion, becomes an important sediment source in the watershed with the increase of rainstorms. Vegetation restoration will reduce sediment transport capacity. With the increasing rainstorm and vegetation restoration in the loess hilly and gully region, the question of whether landslide sediment yield is increasing or decreasing needs to be answered urgently. This study used a Digital Elevation Model (DEM) and a Digital Orthophoto Map (DOM) obtained from remote sensing satellite and UAV photography to interpret the landslide in a small watershed in northern Shaanxi, China. After studying the changes in vegetation and drainage network in 2010, 2015 and 2020, the landslide quantity, area, depth and erosion amount in recent years were explored. The transport of landslide sediment in the watershed is quantified by using the sediment connectivity index, sediment delivery ratio and landslide sediment yield. The results showed that the cropland changed to forest and grassland, and the drainage network continued to shrink with agricultural abandonment. During 2010-2020, the number of landslides increased by 5.88 times and 7.54 times, and the amount of landslide erosion increased by 4.06 times and 4.35 times, but the average area and depth of landslides decreased due to the occurrence of many small landslides on grassland. The sediment connectivity of landslides has been reduced due to the restoration of vegetation and the abandonment of agricultural drainage networks during the conversion of cropland to grassland and forest. Even in the context of increasing landslide erosion, the sediment yield of individual landslides in 2015 and 2020 decreased by 31.43% and 48.37%, respectively. However, the total sediment yield of landslides increased by 3.03 times and 2.89 times in 2015 and 2020, compared with 2010. This study answers the question that landslide sediment yield increases in the loess hilly and gully region under the double background of rainstorm increase and vegetation restoration. This provides a scientific basis for the prevention and control of landslides and the ecological security management of the watershed under the background of climate change.

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# Soil-root shear strength of gullies covered by different vegetation types on the Loess Plateau of China

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**ABSTRACT**

Gully erosion dominates soil degradation in small watersheds. While vegetation mitigates gully development, its effectiveness depends on type, partly through altering soil-root shear strength. Few in-situ studies assess this effect. Hence, this study quantified soil-root shear strength differences between gullies covered by grass versus grass-shrub mixed communities on the Loess Plateau. In-situ shear tests measured peak shear stress (PSS) and displacement, generating shear stress-displacement curves. PSS and strain energy (SE) derived from these curves were calibrated to 15% soil moisture to characterize soil-root shear strength. Results showed the average PSS for grass-covered gullies (9.32 kPa) was significantly higher than for mixed vegetation gullies (6.25 kPa). Shear strength decreased initially then increased with depth. The critical depths for this PSS transition were 20 cm (grass) and 30 cm (mixed). Variations in shear strength with vegetation type and depth were primarily controlled by soil properties and root attributes. PSS exhibited a significant positive association with soil cohesion. SE showed significant positive relationships with root weight mass density and effective root density. Soil organic matter content and aggregate stability enhanced SE through direct and indirect effects. These findings provide insights into the mechanical mechanisms by which vegetation type enhances gully soil strength and controls land degradation in semi-arid regions.

**Keywords:** Gully erosion, Vegetation restoration, Root-soil compound system, In-situ shear test, the Loess Plateau

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# Response of soil erosion resistance to incorporated straw affected by different microbial inoculants in the black soil region of Northeast China

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**ABSTRACT**

Straw incorporation is a widely applied conservation tillage practice that mitigates soil erosion and promotes both the ecological and productive health of the soil. The application of microbial inoculants can stimulate straw decomposition, which benefits soil properties and root traits, and likely further regulates soil erosion resistance, particularly in cold regions. However, the response of soil erosion resistance to straw decomposition influenced by different microbial inoculants remains underexplored. In this study, the flume experiments were conducted to evaluate the influence of straw decomposition on soil erosion resistance under treatments of six microbial inoculants (Chungurun, Fushite, Bangji, Gefu, Hengrun, Lvkang) as well as a control without inoculants in the black soil region of Northeast China. 175 undisturbed soil samples were taken from seven plots and were scoured under five different flow shear stresses. The results demonstrated that microbial inoculants significantly stimulated straw decomposition (15%-36% increase), improved soil cohesion, water stable aggregate, soil organic matter, and root mass density, while reducing penetration resistance. Among six applied microbial inoculants, Lvkang produced the most significant improvements ($p < 0.05$). These improvements contributed to a reduction in soil detachment capacity, ranging from 28.27% to 57.13%. Soil erosion resistance was significantly enhanced ($p < 0.05$). Compared to the control, rill erodibility ($K_r$) decreased by 17.24% to 58.62% and critical shear stress ($\tau_c$) increased by 21.06% to 109.87%. $K_r$ was significantly and negatively correlated to soil cohesion, water stable aggregate, soil organic matter, root mass density and straw decomposition rate ($p < 0.05$), while $\tau_c$ showed no significant correlation with the measured influencing factors. This research provides valuable insights into the application of microbial inoculants for mitigating soil erosion, and offers practical strategies to promote sustainable straw utilization and agricultural management in cold regions.

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# Spatial variation of soil erosion resistance impacted by ephemeral gully on long gentle sloping cropland in the Mollisol region of China

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**ABSTRACT**

Ephemeral gully erosion is a primary driver of soil degradation in cropland, significantly impacting soil properties and crop productivity. These alterations, in turn, profoundly modify soil erosion resistance. Despite its importance for soil conservation, the spatial patterns and underlying driving mechanisms of erosion resistance in long, gently sloping cropland under the influence of ephemeral gully erosion remain poorly understood. This study quantified the spatial heterogeneity of soil erosion resistance in a representative Mollisol region of Northeast China, utilizing in-situ field sampling and controlled flume tests. Dominant factors and their interaction mechanisms were identified, and an estimation model for rill erodibility ($K_r$) was established using stepwise regression based on these drivers. Results indicated that soil erosion resistance varied significantly across slope positions, whereas differences between gully positions were less pronounced. Specifically, $K_r$ increased linearly as gully position descended, while critical shear stress ($\tau_c$) exhibited a "decrease-then-increase" trend, with variations ranging from −2.36 to 50.00. Both $K_r$ and $\tau_c$ followed quadratic relationships with slope position: $K_r$ peaked at the middle slope, while $\tau_c$ reached its maximum at the upper slope. The dominant factors influencing $K_r$ were clay and sand content, soil cohesion (Coh), mean weight diameter (MWD), root mass density (RMD), and straw mass density (SMD), which collectively explained 79% of the observed spatial variability. Notably, SMD exerted a significant regulatory effect on Coh, RMD, and MWD, indirectly mitigating $K_r$ through these integrated pathways (standardized path coefficient = −0.263). The proposed estimation model ($K_r = 0.212MWD^{-2.405}RMD^{-0.502}$) demonstrated robust predictive performance ($R^2$ = 0.860; NSE = 0.863), though further field validation is warranted (Jing et al., 2026). These findings provide a theoretical foundation for site-specific erosion control and contribute to the improvement of process-based soil erosion models in Mollisol regions.

**Acknowledgments**

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# Morphological Development and Hydraulic Characteristics of Plunge Pools in the Gully Beds of Dry Red Soil in Yuanmou Dry-hot Valley

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## ABSTRACT

**[Objective]** Gully head retreat is one of the primary processes in gully erosion, with the continuous erosion of plunge pools caused by gully head jet flow being an important sub-process. However, the development process and morphological characteristics of plunge pools under different jet flow conditions have been rarely reported and remain to be clarified.

[**Methods**] This study selected dry red soil from the gully development area of Yuanmou Dry-hot valley and established a segmented jet flow scouring flume to systematically simulate the development process and morphological characteristics of plunge pools under 5 inflow rates and 4 slope gradients. The hydraulic parameters influencing the morphological development of plunge pools were further analyzed.

[**Results**] The results showed that, except for average depth, all morphological parameters of plunge pools continuously increased. The development rates of length and width were significantly faster than that of depth. The length-to-width ratio gradually increased, and the shape transformed from circular to elliptical. Among all morphological relationships, the best-fitting performance was observed between area and volume ($R^2$=0.80, $P$<0.01). The jet flow velocity at the gully head brink ($V_{brink}$), into the plunge pool's surface ($V_{pool}$), and the distance between jet flow impinging into pool's surface and gully head ($I_{jet}$) all increased with increasing inflow rate and slope gradient, while the angle of the jet flow impinging the pool ($\beta$) showed an opposite trend. All these parameters were more significantly affected by slope gradient. The development rates of plunge pools exhibited a logarithmic relationship with inflow rate and $\beta$, with inflow rate having a stronger influence. The development rates of average depth and backtracking distance exhibited positive power function relationships with Reynolds number ($Re$), flow shear force ($\omega$) and flow power ($P$), while the others showed positive logarithmic function relationships. The retreat process of plunge pools exhibited a stepwise development pattern. The retreat rate increased significantly with the enhancement of hydraulic action, while $I_{jet}$ also increased notably, and both factors jointly influenced the plunge pool retreat process.

[**Conclusion**] These findings contribute to a better understanding of plunge pool development and provide a basis for improving gully head retreat models.

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# Green-Ampt infiltration model calibration on a Peruvian Andean hillslope under different land uses

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## ABSTRACT

Water infiltration into soil is a key process in irrigation, erosion and soil/water management studies. In the Peruvian Andes context, soil hydraulic properties are virtually unknown, and their characterization is challenging due to stony soils and steep slopes. Several field methods have been developed including double-ring and single-ring infiltrometers. The Green–Ampt infiltration model [1], derived from Darcy's law, is widely used to simulate infiltration processes. The objective of this study was to calibrate the Green–Ampt model using field infiltration experiments in order to provide parameters suitable for Andean conditions and to evaluate differences in model applicability across land uses. The study was conducted in the community of Yacuy, Huancavelica department (center of Peru). Six land uses were selected: Shrub natural regeneration, two Grazing areas, Irrigated Lucerne, Avocado orchard with cattle grazing, and Natural Forest. For each land use, six single-ring infiltration tests [2] were performed. After the infiltration tests, soil samples were collected to determine bulk density and particle-size distribution. Saturated hydraulic conductivity (*Ks*) was estimated using the Rosetta pedotransfer function [3]. The Green–Ampt model was calibrated by optimizing the matric potential at the wetting front (*hf*) through minimization of the sum of squared logarithmic residuals (SSR) using R software.

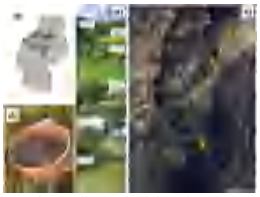


Figure 1. Composite image showing: (a) location within the Huancavelica Department (center of Peru); (b) photographs of each evaluated land use; (c) mountain landscape perspective; and (d) single-ring infiltration test

| Land use | Sand | Silt | Clay | *Ks* | θi | θf | Bulk density | SSR | *hf* |
|---|---|---|---|---|---|---|---|---|---|
| - | - | - | - | mm/sec | - | - | g/cm³ | - | mm |
| Use 1 | 51.5 | 22 | 51.5 | 0.0009 | 0.2020 | 0.0451 | 1.3 | 0.0884 | 150532.0 |
| Use 2 | 32 | 39.25 | 30.75 | 0.000282 | 0.3192 | 0.0232 | 1.63 | 0.0004 | 2035.2 |
| Use 3 | 37 | 35.25 | 42.75 | 0.000613 | 0.3466 | 0.0446 | 1.5 | 0.0308 | 50471.7 |
| Use 4 | 38.75 | 37.25 | 36 | 0.002708 | 0.4266 | 0.0490 | 1.26 | 0.0109 | 5442.7 |
| Use 5 | 21.5 | 17.75 | 57.75 | 0.000982 | 0.3937 | 0.0509 | 1.11 | 0.0183 | 10500.2 |
| Use 6 | 20 | 37.5 | 50.5 | 0.001182 | 0.3565 | 0.0853 | 1.26 | 0.0179 | 9028.6 |

Table 1. Green–Ampt model calibration parameters and fit metrics

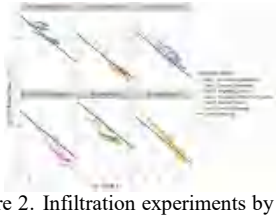


Figure 2. Infiltration experiments by land use

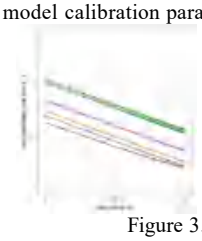


Figure 3. Land-use specific Green–Ampt model calibration

The Green–Ampt model showed a good fit, with SSR values close to zero across land uses. The best performance is observed in Avocado orchard with cattle grazing. A gradient of high calibrated *hf* values was identified. Land uses with low management intensity, such as shrub regeneration and natural forest, exhibited the highest infiltration rates, favoring water redistribution during intense and potentially erosive rainfall events. In contrast, soils under grazing and cattle presence showed the lowest infiltration rates, indicating soil compaction caused by management practices. Overall, the results demonstrate that the Green–Ampt model is a viable tool for studying infiltration processes in Andean environments. However, the scarcity of methodologies adapted to mountainous conditions and the limited availability of reliable soil hydraulic data remain major challenges for hydrological studies in the region.

**Acknowledgments**
To Universidad Nacional del Centro del Peru

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# Study on the dynamic changes in soil erosion and the stability of the soil organic carbon pool in the surface layer of purple soil on the slopes implemented the Grain-for-Green project

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**ABSTRACT**

The Grain-for-Green Program (GFGP) has significantly enhanced ecosystem service values by changing land use and vegetation cover characteristics, such as reducing soil erosion and increasing soil carbon sequestration. These benefits of the GFGP primarily occur within the topsoil layer, and are not entirely independent, as they can mutually reinforce each other through coupled interactions. However, in the present researches, the processes and mechanisms influencing the soil organic carbon pool by the erosion reduction effect of the GFGP remain unclear. Therefore, cultivated land, land where the GFGP has implemented for 25 and 50 years (GFGP25 and GFGP50), and forest land in purple soil areas were selected to investigate the impacts of the GFGP on soil erosion and SOC dynamics via combined application of 137Cs and 210Pbex in the Sichuan Basin, Southwest China. Compared to lands before GFGP implementation, the soil erosion rates were significantly reduced by 72.50% to 327.18% and 88.66% to 540.35% in GFGP25 and GFGP50, respectively. Compared to cultivated land, GFGP50 and forested land significantly increased the average SOC content, with increases of 59.47% and 101.42%, respectively. Meanwhile, the GFGP could significantly increase the macroaggregate SOC. Moreover, the GFGP can also significantly increase the POC and MAOC content in the surface soil, with a notably higher increase in POC. Compared to cultivated land, the POC contents in the surface soil of GFGP50 and forested land increased by an average of 317.65% to 499.66%, with an average increase in POC/MAOC of 285.71% to 385.71%. Erosion reduction via GFGP could significantly enhance soil carbon sequestration in the eroded zones. In lands of GFGP, soil erosion processes explained 12.16% of the variation in SOC and its physical fraction stock in the surface soil. Carbon sequestration processes were significantly different between erosion and sedimentation zones. Microaggregate organic carbon (MIC) could significantly influence POC content in erosion zones, but its effects on both POC and MAOC were insignificant in sedimentation zones.

# A Dynamic Gully Erosion Risk Assessment Framework Considering Rainfall Regime Shift in the Songnen Typical Black Soil Region

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**ABSTRACT**

Soil erosion is the dominant form of land degradation in the Songnen typical black soil region. Specifically, gully erosion, as the most severe form of water erosion, has emerged as a critical bottleneck constraining sustainable agriculture, posing a serious threat to regional food security and ecological stability. Nevertheless, current gully erosion risk assessments remain predominantly confined to static susceptibility mapping. Crucially, these approaches fail to account for the dynamic variations in erosion thresholds driven by rising erosive rainfall events and annual precipitation under climate change, leading to significant biases with reality. Leveraging 2010 and 2020 Google Earth imagery coupled with field surveys, we constructed two datasets: historical gullies, reflecting long-term morphological evolution, and newly formed gullies, capturing decadal-scale erosion driven by climate change. We then evaluated the predictive performance of six machine learning models (GBDT, XGB, RF, KNN, MLP, and LR) and two Stacking ensemble models for gully erosion risk assessment. By integrating the optimal model with the two datasets, we developed a novel gully erosion risk assessment framework. This framework was utilized to characterize the spatial heterogeneity of gully erosion risks and driving factors in the Songnen typical black soil region. The results demonstrated that: (1) The Random Forest (RF) model outperformed other algorithms in assessing both gully erosion susceptibility and potential, with AUC values reaching 0.975 and 0.979, respectively; (2) The Quantile method emerged as the optimal classification approach, while the Natural Breaks method offered superior stability. Notably, 61.45% of the study area is classified as high-risk or higher, highlighting an urgent need for erosion control measures; (3) SHAP analysis revealed that Mean Annual Precipitation (MAP) and Stream Power Index (SPI) co-dominate gully erosion risk, exhibiting distinct threshold effects. Notably, the relative importance of Topographic Position Index (TPI) and Human Footprint (HFP) was significantly higher for gully erosion potential than for susceptibility. This suggests that topographic transitions and anthropogenic disturbances amplify the erosive impact of rainfall pulses. These findings not only deepen our understanding of gully erosion dynamics in the Songnen black soil region but also provide a scientific basis for the precise allocation of regional soil and water conservation measures.

**Acknowledgment**

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# Effects of Farmland Shelterbelt Distribution on Wind-Water Compound Erosion in the Northeast Black Soil Region of China

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**ABSTRACT**

Severe soil degradation resulting from wind-water compound erosion poses a significant challenge to food security. Although farmland shelterbelts were originally established to reduce wind erosion, the influence of their spatial layout on the effectiveness of a windbreak requires further evaluation. More importantly, with variations in topography, how the direction of shelterbelts affects soil water erosion processes remains unclear. To address these issues, in this study, the effects of shelterbelt arrangements on wind and water erosion in the typical black soil region of northeastern China were systematically assessed through a sampling survey and remote sensing image interpretation combined with meteorological data and topographic information. The results revealed that the wind erosion intensity increased from northeast to southwest across the region. Shelterbelts effectively control wind erosion, with particularly better effects in areas experiencing severe wind erosion, but its orientation on sloping croplands often constrains ridge direction. In the northern region, most shelterbelts were aligned parallel or perpendicular to the hillslope, whereas in the south, the shelterbelt layout generally disregarded topographic conditions. Under the influence of established shelterbelts, the direction of the ridge tillage was mainly parallel or perpendicular to the shelterbelts. This configuration promotes cross-slope and up-and-down slope ridge tillage, both of which significantly intensify rill/inter-rill erosion and gully erosion. In addition, snowmelt runoff is a major driver of water erosion in high-latitude regions. Shelterbelts influence snow redistribution patterns, thereby modifying snowmelt-driven runoff and soil erosion processes. Gullies affected by shelterbelt-induced snow redistribution exhibited area expansion rates approximately 1.6 times higher than those unaffected. The research results indicated that the layout of farmland shelterbelts in the typical Northeast Black Soil Region may exacerbate water erosion on sloped farmland, providing new guidance and References for shelterbelt restoration and gully management.

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# Changes in soil aggregates, pore characteristics, and their relationships with soil erodibility in periodically submerged soils. A case of the Water Level Fluctuation Zone in the Three Gorges Reservoir, China

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## ABSTRACT

Regulation of the water level fluctuation in the Three Gorges Reservoir (TGR) can critically affect ecological degradation, particularly soil health through its direct impacts on aggregates and indirectly due to erosion. Over the last two decades, distinct elevations in this region experienced different levels of water residence time and intensity, which could be based on to understand the effects of hydrological alterations on soil structural properties. This study has relied on long-term monitoring data of the hydrological alterations in the TGR to evaluate the impacts of water level fluctuations on soil aggregate stability, pore number, porosity, and erodibility. The study has further assessed how soil aggregate stability influence soil erosion and pore characteristics in periodically flooded soils. Samples from different elevations (155 m, 160 m, 163 m, 166 m, 172 m, and 180 m) in the water level fluctuation zone (WLFZ) were exposed to continuous wet-shaking for 3, 9, 27, 54, and 81 minutes resulted to different WLF intensity accordingly. The results showed a remarkable difference between aggregates size before and after the experiment due to the observed increase in micro-aggregates (<0.25 mm) and decrease in large macro-aggregates (>5mm and 2-5mm), respectively. High proportions of micro-aggregates gradually reduced along the elevations, suggesting the capability of soil aggregates from higher and control elevations to withstand stress. The mean weight diameter (MWD) was significantly lower in the lower (2.4–3.7 mm) compared to upper (5.3–6.0 mm) elevations. The exponential prediction proved that aggregate stability decreased with the increase of WLF intensity, insisting the effects of continuous hydrological stress to aggregate break-down. The Disintegration rate (Dr) and soil erodibility (k) showed a positive relationship, $R^2 = 0.73$ ($p < 0.05$). The soil properties decreasing Dr similarly decreased soil erodibility in the study area. Predominant distribution of macropores was recorded in lower elevations, while micropores were widely distributed in the upper elevations. The increase in MWD has increased the proportion of micropores, with $R^2 = 0.59$. This could suggest that the decrease in flooding intensity can create favorable conditions for plant roots growth. The strong flooding stress in lower elevations accelerated the disintegration of soil aggregates and considerably increased the formation of macropores due to slaking and cracking. Relying on the present findings, environmental problems mostly soil erosion in the TGR could be linked to excessive destabilization of soil aggregates. Therefore, the results of this study emphasize the need to restore degraded soils in periodically submerged environments by implementing vegetation restoration measures. This could enhance and sustain aggregate stability, which was also proved to increase functional pores and minimizes soil erosion under hydrological alteration conditions.

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# Technical Feasibility of Biomass Buffer Strips for Capturing Excess Nutrients from Agricultural Runoff

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## ABSTRACT

Buffer strips are widely recognized as effective landscape measures for intercepting nutrient losses from agricultural fields, thereby enhancing ecosystem protection [1]. However, conventional riparian buffers are spatially restricted, with land-use competition and maintenance demands hindering their broader adoption. To address these limitations, this study introduces the innovative concept of biomass buffer strips, which extend the principle of phytoremediation by employing perennial vegetation to actively capture and utilize excess nutrients for plant growth while producing renewable biomass with economic value through their marketing potential. Thus, biomass buffer strips represent an approach that offers both environmental and economic benefits and can also be implemented along upland field margins that are not directly adjacent to water bodies. This study aims to evaluate the technical feasibility of perennial biomass buffer strips in agricultural fields to mitigate phosphorus (P) losses via surface runoff and subsurface flow, thereby preventing eutrophication of water bodies. To achieve this goal, the study follows a two-pronged approach: the uptake rate of P by biomass vegetation, including switchgrass and miscanthus, is quantified through greenhouse column experiments (Fig. 1); and the relationship between plant-available P retained in soil and dissolved reactive phosphorus (DRP) transported by surface runoff is determined through field trials that incorporate relevant environmental covariates. These approaches quantify the retention and transformation of excess P at different experimental scales, providing empirical evidence for the potential of biomass vegetation to intercept and utilize excess P before its transport to downstream waters.

This study closely aligns with the conference theme by demonstrating a nature-based solution for reducing nutrient pollution from agricultural lands. The findings highlight nutrient interception and transformation within biomass buffer systems, demonstrating their multifunctional role in coupling nutrient recovery with renewable biomass utilization and ultimately promoting the wider adoption among stakeholders.

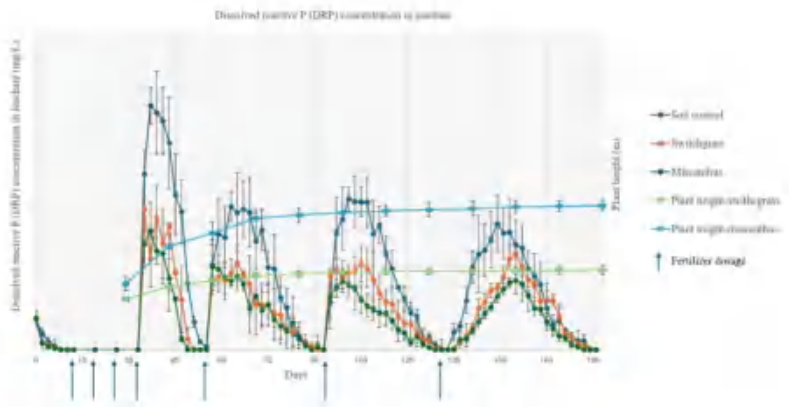


Fig. 1. Leachate DRP concentrations and biomass plant growth across four fertilizer cycles.

**Keywords:** Phosphorus (P), Eutrophication, Phytoremediation, Biomass buffer strips.

**Acknowledgments**

This work is supported by the Ontario Ministry of Agriculture, Food and Agribusiness.

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# Management-Induced Changes in SOM Composition Control Soil Wettability and Hydrological Function

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**ABSTRACT**

Soil health is functionally governed by soil organic matter (SOM), yet the composition of SOM, not just its total quantity, dictates key soil physical properties and hydrological processes. A critical knowledge gap exists in quantitatively linking agronomic management to specific SOM chemical compositions and, in turn, to soil hydrological functionality (e.g., infiltration and water retention). This study investigated these linkages in a long-term agricultural experiment in a humid-temperate ecosystem (Tennessee, USA).

We collected surface soils (0–5 cm) from six contrasting management regimes, including conventional tillage (CT), no-till (NT), cover crops (CC), and poultry litter (PL) applications. We evaluated soil physical functionality by measuring wettability (Water Drop Penetration Time - WDPT, contact angles) and linked these physical properties to SOM quantity and chemical composition (particulate vs. mineral-associated fractions).

Our preliminary results demonstrate that management is the dominant control on soil wettability. We found that management systems with high biological inputs (e.g., NT + CC + PL) fostered the accumulation of hydrophobic SOM compounds, resulting in water repellent soils (WDPT > 5s) with high contact angles. This physical state promotes rapid, non-uniform infiltration. Conversely, conventionally tilled systems with limited organic input exhibited no hydrophobicity but had slower infiltration.

This work provides direct evidence linking specific management practices to distinct SOM chemical signatures, which in turn control fundamental soil physical properties. This mechanism is a key driver of the soil's hydrological functionality and its subsequent ability to capture and store plant-available water.

**Acknowledgments**

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# From Soil Morphology to Depression Hydrology: Diagnostic Criteria and Predictive Patterns in the Oka-Don Lowland

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**ABSTRACT**

Hydrological processes organize the soil cover of the Oka-Don Lowland, where a depression microrelief creates a unique mosaic of soil-vegetation complexes. While similar landscapes exist in the Canadian Pothole Region and Polish lowlands, the distinct moisture and temperature regimes of the Oka-Don region shape unique hydrological processes and pedogenesis.

Depression and inter-depression soils are functionally linked: surface runoff accumulates in depressions, waterlogging their soils, while maintaining optimal moisture in inter-depression spaces. This promotes Chernozem formation in inter-depression areas, while depressions develop waterlogged soils that, despite poor agricultural suitability, perform crucial hydrological functions, serve as biodiversity hotspots, and indicate depression hydrology.

This study developed approaches to reconstruct and predict depression water regimes through integrated analysis of soil morphology and landscape parameters. Objectives included: 1) investigating depression soil morphology; 2) linking soil morphology to water regime characteristics; 3) identifying landscape factors to predict water regimes in unstudied depressions.

Analysis of nine depressions revealed that soils form a genetic sequence reflecting waterlogging source and duration. Gleysols develop under permanent surface and groundwater saturation, Stagnosols form under periodic surface and groundwater influence, while Planosols occur under exclusively surface-driven waterlogging. Waterlogging duration decreases along the sequence: Gleysols → Stagnosols → Planosols.

Simple morphometric parameters (volume, catchment area, depth of depressions) failed to reliably differentiate the depression soils at this key site. However, integrated analysis incorporating precipitation and moisture accumulation data revealed clear patterns. The most waterlogged depressions with Gleysols occupy lower hypsometric positions, characterized by larger diameters and predominantly greater volumes, with strong surface waterlogging (water layer up to 0.3 m) and tall hydrophilic herbaceous plants. Depressions with Stagnosols show intermediate characteristics, supporting distinct vegetation zonation with Cyperaceae in central areas and Salix on slopes. The driest depression with Planosols displays minimal morphometric values and weak surface waterlogging (water layer ≤0.1 m). In these areas, vegetation extracts moisture from surface horizons through herbaceous roots and from deeper layers via woody taproots, enhancing soil desiccation.

The developed approach effectively diagnoses and predicts water regimes in depression landscapes. Quantitative relationships between soil indicators, topography, and vegetation characteristics provide a basis for spatial extrapolation of these patterns.

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# Sensor-Based Modeling of Soil-Water Dynamics for Irrigation and Subsurface Hydrology

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**ABSTRACT**

Sustainable soil and water management in arid regions requires precise quantification of water fluxes across the soil-plant-atmosphere continuum. This study presents an integrated framework that combines soil moisture-based Evapotranspiration (SMET) modeling, a water-salt-biomass balance approach, sub-surface hydrology sensing, and socio-technical analysis to optimize water use efficiency (WUE) in Utah's agricultural systems. Multi-year field trials evaluated crop-irrigation systems under drought-tolerant genetics, deficit irrigation levels, and conservation practices. The SMET model accurately estimated actual ET ($R^2$ = 0.98-1.0) across management scenarios, identifying low-elevation sprinklers with moderate deficit irrigation as optimal for improving WUE (Singh et al., 2025). A novel water-salt-biomass balance was used to quantify the leaching fraction and deep percolation. The balance links solute transport and biomass accumulation to partition applied water into productive and leaching losses. Field-measured soil moisture and matric potential data were fitted using improved van Genuchten (VG) and Peters-Durner-Iden (PDI) models to refine retention and conductivity parameters, enabling real-time flux estimation via Buckingham-Darcy's law. These coupled modules bridge infiltration, ET, percolation, and recharge to establish a transferable framework for field-scale water accounting. A parallel socio-technical study identified barriers and incentives for sensor adoption, illustrating how integrating biophysical modelling with behavioral insights supports scalable, data-driven irrigation management that enhances groundwater sustainability and agricultural resilience.

**Keywords:** Actual evapotranspiration, soil water retention, deep percolation, groundwater recharge, and sensor adoption.

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# Leveraging Multi-Temporal Environmental Data in a Long Short-Term Memory Model for Groundwater Nitrate Prediction

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**ABSTRACT**

Groundwater nitrate concentration constitutes an environmental risk, particularly in regions with significant agricultural activity, livestock production and variable climatic conditions. The Veneto region in northeastern Italy is characterized by high agricultural production and complex hydrogeological systems that could have led to nitrate transport into groundwater. To address concerns about increased nitrate concentrations, the European Union implemented the Nitrates Directive (91/676/EEC), which aims to protect and improve water quality by regulating agricultural practices and designating Nitrate Vulnerable Zones (NVZs). Despite ongoing mitigation efforts under the Nitrates Directive, more advanced tools need to be applied in the Veneto region to understand nitrate variability across different spatial and temporal scales. In response, this study developed a Long Short-Term Memory (LSTM) neural network to predict nitrate concentrations in the groundwater of Veneto. The neural network utilizes a comprehensive dataset spanning 21 years (2003-2023) from 150 wells sampled in the spring and fall of each year. The model integrates an extensive set of predictive variables to capture temporal, spatial, and environmental differences. These include meteorological variables aggregated across 12 time intervals, soil properties at two depths, topographic attributes, soil erosion factors based on the Revised Universal Soil Loss Equation (RUSLE), land use and agricultural land cover within five spatial buffers, nitrogen and irrigation inputs, net primary productivity, population density, and well characteristics. The LSTM was able to capture temporal patterns and interactions among predictor variables to assess how short- and long-term patterns influence nitrate levels. The large, multi-scale dataset could detect seasonal, interannual, and spatial variability specific to the Veneto region. This study demonstrates the potential of machine learning techniques to advance nitrate risk assessment, contribute to data-driven groundwater quality modeling in complex agricultural regions, and aid in site-specific management strategies within the context of the Nitrates Directive.

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# Leptosols of Subarctic barrier islands: land – sea interface

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**ABSTRACT**

The barrier islands in the Northern Okhotsk Sea are unique landscapes, which soils develop on sands and pebble under regular reshaping and addition of marine material by storm surges and tides. These are low, elongated landforms 0-5 m a.s.l. with Calamagrostis-Leymus meadows. The soil profile comprises an organic "dry-peat" horizon merging into pebble interlaced with living and dead roots. Good drainage is provided by marine weakly stratified pebble and despite the periodical ingress of sea waters. Aerated moisture-unstable environment is persistent in these soils. Soil development proceeds slowly and discontinuously, with frequent partial removal of the upper horizons owing to tides and surges. The marine effects on the environment also comprise sea salts emission, and numerous dense seagull colonies are common.

The influence of sea waters on barrier islands does not produce soil hydromorphism, and it creates problems for their classification. The absence of prolonged waterlogging required for peat formation, hence, histic horizon in the WRB system, does not permit to qualify them as Histosols; their topsoil is defined as dry-peat horizon in the Russian classification system. It consists of weakly decomposed plant residues with fibric fabric, abounds in roots and is in agreement with cold, humid, and oxygen-rich environment. It functions as moisture reservoir, maintains vegetation stability and contributes to fixation of sand and pebble brought by surges.

As a result, we have an oxymoron situation: non-hydromorphic soils occur under conditions that are, in fact, strongly hydromorphic. How can we classify them? Depending on the degree of profile development and substrate stabilization, soils were identified as follows: Coarsic Skeletic Eutric Leptosols (Fluvic, Ornithic, Protic) on recently reworked surfaces, Coarsic Skeletofolic Eutric Leptosols (Fluvic, Ornithic) on relatively stabilized material. The most developed soils are Coarsic Skeletofolic Dystric Leptosols (Fluvic, Protospodic). This sequence reflects both the duration of surface stability and the decrease of marine effects.

The studied soils occur at land – sea interface: they are not submerged or anaerobic, but are shaped by coastal processes. Their morphology and genesis demonstrate how pedogenesis proceeds under permanent marine influence and periodical reworking by storms and tides.

The example of these soils extends the concepts of hydromorphic and submerged soils in tidal zones of Subarctic seas.




Figure 1. Coarsic Skeletofolic Dystric Leptosol (Fluvic, Protospodic)




Figure 2. Skeletofolic material (upper picture), protospodic feature on pebble surface (lower picture)

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# A challenging prediction: The heterogeneous nature of preferential flow masked by homogeneous moisture sensor responses

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## ABSTRACT

Soil water dynamics in the unsaturated zone are strongly influenced by complex flow phenomena, particularly preferential flow (PF), which can bypass the soil matrix and complicate interpretation of soil water content measured at high temporal resolution. Detecting PF requires alignment between process and observation scales so that predictive models can represent Pedon-scale flow complexity.

For a soil water content data set collected over two years at 10-minute measurement intervals in a humid-temperate Andosol in southern Chile, where PF studies are limited, we applied two PF identification methods, the velocity threshold (VT) and the non-sequential response (NSR), alongside detailed rainfall and wetting-process characterisation. VT and NSR differ in detection sensitivity. Because wetting responses and PF triggers are not unique, we used variable-selection tools: correlation matrices, principal component analysis (PCA), and random forests (RF). We analysed 158 rainfall events (≥2 mm), 95 of which produced wetting responses. These were detected with eight TEROS- 12 sensors at 10, 20, and 60 cm depths (3, 3, 2 replicates). One TEROS-21 sensor per depth monitored the matric potential. In situ hydraulic conductivity was estimated using field dual-porosity van Genuchten parameters.

Correlation matrices revealed an inverse relationship ($r = -0.68$; 20 cm depth) between initial soil water content ($\theta$start) and the time-integrated coefficient of variation (CVint), confirming that dryness dictates heterogeneity. PCA identified three orthogonal factors: rainfall-to-wetting response, soil hydraulic state, and infiltration dynamics. The infiltration velocity (Vinf) was structurally independent of all three. VT indicated PF in 37% of wetting events, whereas NSR detected only two events, proving unsuitable for our dataset. The 6-hour rainfall separation requires reconsideration, as soil water redistribution between events produced false-positive NSR detection. RF regression ($R^2 = 0.93$) showed Vinf was dominated by precipitation rate (Prate), with $\theta$start showing negligible predictive value. RF classification predicting PF occurrence (VTPF) achieved high performance (balanced accuracy = 92.7%). However, the predictive hierarchy reversed: occurrence was best predicted by soil state variables (hydraulic conductivity at 10 and 20 cm depth, and hydraulic gradient), while Prate dropped in rank.

PF occurred most frequently under wetter conditions, primarily governed by rainfall kinetics. Yet, sensor signals appeared largely homogeneous, masking PF occurrence. Conversely, spatial heterogeneity is highest under dry conditions. The NSR method requires detectable heterogeneity and may be better suited for events under dry soil conditions. This highlights the challenge of predicting PF and the need to define PF by both its kinetics (Vinf) and spatial signature (CVint) to identify scalable trends.

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# Tree parasitism as a microclimatic amplifier: implications of Viscum album infection for soil moisture and repellency dynamics

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**ABSTRACT**

Mistletoe (*Viscum album sp.*) is a widespread hemiparasitic species whose physiological interactions with host trees can indirectly modify forest microclimates and soil hydrological behavior. This study examined how mistletoe infection affects temperature, soil moisture dynamics, and soil physicochemical properties in Abies and Pinus forest ecosystems.

Measurements conducted between April and August 2025 revealed that in Abies stands, infected trees showed 1.0 - 2.1 °C higher air and soil temperatures and up to 12 % lower mean soil moisture compared to areas under healthy trees. Correlation analysis ($r = 0.62$ for healthy vs. $r = 0.28$ for infected sites) indicated that the presence of mistletoe weakens the coupling between soil temperature and moisture. These conditions may promote temporary soil water repellency and reduced wettability following drying events, especially during low-rainfall periods.

In contrast, Pinus ecosystems exhibited higher hydrological stability, with temperature differences below 0.5 °C and stable volumetric water content ($r > 0.70$). This resilience is likely related to denser ground vegetation and the lower physiological sensitivity of pine species, which buffer microclimatic variation. No immediate degradation of soil health indicators (organic carbon, electrical conductivity, or cation exchange capacity) was detected; however, changes in moisture - temperature interactions suggest potential shifts in infiltration and nutrient mobility over time.

The results indicate that mistletoe presence, while not a direct driver of soil water repellency, acts as a microclimatic amplifier, creating conditions conducive to transient repellency and altered water infiltration in sensitive forest soils. Understanding these host-dependent feedbacks between canopy parasitism, soil water behavior, and nutrient cycling is crucial for predicting long-term forest ecosystem resilience under climate change.

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# Salinity-Tile Drainage Linkages and their Impacts on Soil Health in the Red River Valley (United States)

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**ABSTRACT**

Soil salinity is a persistent and spatially variable constraint on crop productivity and soil health across the Red River Valley (RRV) and similar landscapes of the Northern Great Plains. Saline soils with electrical conductivity greater than 1.7 dS $m^{-1}$ have been shown to reduce corn yields. Although over 80% of the land in the RRB is dedicated to agricultural production, primarily corn, soybean, small grains, and specialty crops, more than 26% of this region is affected by salinity that limits crop growth. Additionally, the adoption of tile drainage has nearly tripled in the past decade. Despite decades of field trials and remediation efforts, outcomes have been fragmented due to site-specific variability, shallow water tables, complex geology, hydrology, and inconsistent resources.

This work addresses these challenges by using an enhanced modeling framework to integrate long-term field observations and remote sensing data to tile drainage impacts on salt fate, transport, and leaching under diverse soil, landscape, and management conditions. We performed a comprehensive regional assessment of tile drainage-salinity interactions and their potential impacts on crop productivity across the RRV. By linking field-scale processes with watershed-scale responses, the modeling framework provide a decision-support tool for assessing trade-offs between salinity mitigation, crop productivity, and water quality outcomes.

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# The influence of selected factors on the various phosphorus compounds in soils with a bog iron ore horizon

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**ABSTRACT**

Soils containing bog iron horizons occur relatively commonly, although they are usually limited to small areas within river valleys and in the vicinity of water bodies in central and northern Europe. The formation of bog iron is associated with redox processes involving the mobilization and accumulation of iron compounds. These processes are accompanied by the concentration of other elements, including phosphorus. An analysis of the distribution of phosphorus compounds in soils with bog iron horizons (at different stages of development) and in iron-rich soils lacking continuous bog iron layers is of particular interest, as it allows for the assessment of pedogenic processes occurring in these soils.

Total phosphorus ($P_{tot}$) was determined using X-ray fluorescence spectrometry (XRF). Mineral phosphorus forms were analyzed according to the Chang and Jackson (1957) fractionation method, yielding seven fractions associated with iron, aluminum, and calcium compounds. The total phosphorus content in bog iron horizons ranged from 0.58% to 2.43%. A strong positive correlation was observed between $P_{tot}$ and total iron content (Fe), with a correlation coefficient of 0.95.

Occluded phosphorus compounds dominated both the bog iron horizons and the overlying surface horizons, accounting for more than 50% of all mineral phosphorus forms. The content of occluded phosphorus was also correlated with iron, most strongly with the dithionite-extractable iron fraction (Fed), with a correlation coefficient of 0.84. The remaining phosphorus forms were primarily associated with oxalate-extractable iron (Feo), whereas Ca-bound phosphorus (Ca–P) showed a strong correlation with pyrophosphate-extractable iron (Fep), a form linked to soil organic matter ($r = 0.82$). These results indicate highly complex relationships between phosphorus, iron, and other environmental components in soils containing bog iron horizons.

# Occurrence and assessment of water repellency in biochar and biochar-amended soils

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**ABSTRACT**

Soil water repellency occurs widely from the nanoscale to the ecosystem scale, is closely associated with soil moisture and its spatial distribution and significantly influences soil hydrological processes. Contact angle (CA) method and water drop penetration time (WDPT) method are commonly used to determine soil water repellency; however, inconsistent results are frequently observed for biochar when using these two methods, reducing the accuracy and comparability of assessments. Moreover, the regulatory effects of biochars with diver structures on soil water repellency lack systematic quantification.

In our study, a series of pure substances were first employed as model materials to establish a new method for evaluating their hydrophobicity. Subsequently, biochars with different feedstock sources and pyrolysis temperatures were compared to characterize surface structural differences. We analyzed the effects on the occurrence and intensity of biochar hydrophobicity and investigated the change of soil water repellency within 90 days after biochar amendment. Based on changes in CA during water droplet spreading within 90 s, a dynamic contact angle (DCA) method was developed, and the concept of "pseudo-hydrophobicity" was proposed for the first time[1]. Application of the DCA method effectively reconciled discrepancies between the CA and WDPT methods in determining the water repellency of biochar and biochar-amended soils. It demonstrated that pyrolysis-induced variations in surface functional groups, specific surface area, and pore size distribution are the key factors controlling biochar hydrophobciity[2]. These structural characteristics exhibited significant negative correlations with water repellency ($p < 0.05$). In biochar–soil incubation experiments, the addition of most biochars increased the contact angle of soil within 90 s, transforming originally hydrophilic soils into a 'pseudo-hydrophobic' state. This study proposes and validates the DCA method as a novel approach for evaluating the water repellency of biochar and biochar-amended soils, providing methodological and technical support for biochar selection and its soil application.

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# Characteristics, Driving Mechanisms, and Machine Learning Modeling of Nitrogen Runoff Losses from Chinese Rice Cropping Systems

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**ABSTRACT**

Clarifying the characteristics, mechanisms, and spatial patterns of nitrogen (N) runoff loss in rice cropping systems is crucial for optimizing agricultural N management strategies and controlling non-point source pollution in China. However, the key factors and how they determine N runoff loss in rice cropping systems, remain unclear at a national scale. In this work, we compiled a comprehensive dataset comprising 1,154 records of N runoff losses from Chinese rice cropping systems, synthesized from 141 published studies. Piecewise structural equation modeling (SEM) was first applied to examine the causal linkages among key factors and their effects on N runoff losses in rice cropping systems. Based on the key factors, machine learning models were subsequently developed to simulate N runoff losses across Chinese rice-growing regions. The results showed that the average N runoff loss across the compiled dataset was 9.52 kg N $ha^{-1}$ $season^{-1}$ in Chinese rice cropping systems, with significantly higher N runoff losses observed in the paddy rice system (PRS) than in the paddy rice–upland rotation system (PRURS). Random Forest–based ranking and SHAP (SHapley Additive exPlanations) interpretations of the machine learning model determined that precipitation, N fertilization rate, and total soil N (TSN) were identified as key influencing factors for N runoff loss, and soil elemental stoichiometric ratios (e.g., C:N:P) were negatively correlated with N runoff loss, the later factors highlighted the importance of soil biogeochemical cycling in regulating N runoff loss in the Chinese rice cropping systems. The Piecewise SEM suggested that the pathway effects of the composite variables of N fertilization rate, soil nutrient properties, and soil C:N:P on N runoff loss were ranked as follows: Fertilization (0.52) > Soil nutrient properties (0.29) > Soil C:N:P (-0.14), in the Chinese rice cropping systems. The pathway effects of the three composite variables were ranked as Fertilization (0.52) > Soil nutrient properties (0.38) > Soil C:N:P ratio (-0.19) in the PRS, and Fertilization (0.52) > Soil nutrient properties (0.13) > Soil C:N:P ratio (-0.10) in the PRURS. This indicate that soil nutrient properties and the soil C:N:P ratio exert stronger effects on N runoff loss in the PRS than in the PRURS. The XGBoost model estimated that over the period 2018-2022, the average N runoff loss in Chinese rice cropping systems was 6.64 ± 3.73 kg N $ha^{-1}$ $yr^{-1}$, corresponding to a total runoff load of 228.62 ± 27.43 Gg N $yr^{-1}$. Single- and double-cropping systems exhibited runoff loss intensities of 6.26 ± 3.31 and 11.77 ± 5.07 kg N $ha^{-1}$ $yr^{-1}$, respectively, and the N runoff load of early rice was 1.57 times that of late rice (17.05 ± 1.09 vs. 10.86 ± 2.59 Gg N $yr^{-1}$). High runoff loss intensities were concentrated along the 30°N belt and in southern coastal regions. Hainan Province exhibited the highest intensity (12.02 kg N $ha^{-1}$ $yr^{-1}$), while Hunan and Jiangxi each accounted for more than 10% of the national N runoff loss load. Under a scenario of 15% N reduction, the national N runoff loss intensity and load were projected to decrease by 0.60 kg N $ha^{-1}$ $yr^{-1}$ and 20.45 Gg N $yr^{-1}$, respectively, equivalent to an 8.94% reduction. Early rice showed a higher mitigation potential than late rice (11.03% vs. 7.09%), and provinces with high N fertilizer application rates such as Hubei, Jiangsu, and Shanghai demonstrated more significant reductions. These results provide critical insights into assessing N runoff loss, and offer a robust basis for efficiently mitigating N runoff losses and optimizing N management strategies to control agricultural non-point source pollution in Chinese rice cropping systems.

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# Machine Learning–Based Modeling of Phosphorus Runoff Losses and Their Component Fractions in Chinese Rice Cropping Systems

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## ABSTRACT

Identifying the key controlling factors and accurately assessing phosphorus (P) runoff loss and its component fractions—total phosphorus (TP), dissolved phosphorus (DP) and particulate phosphorus (PP)—from rice cropping systems are crucial for controlling agricultural non-point source pollution in China. In this study, we compiled a comprehensive dataset comprising 517 field observations from Chinese rice cropping systems, and developed six machine learning (ML) models to simulate the intensity and load of TP, DP, and PP runoff losses across the China and its six major rice-growing zones (categorized as zone I to VI); especially, a Bayesian correction method combined with Monte Carlo spatial validation was employed to adjust DP and PP estimates to satisfy physical constraints in the ML model. The Pearson correlation analysis demonstrated that TP runoff loss exhibited a significant positive correlation with precipitation and P fertilization rate, while correlations with other factors were generally not significant. However, DP runoff loss was linearly and positively correlated with soil organic carbon (SOC), total soil nitrogen (TSN), and total soil phosphorus (TSP), but negatively correlated with soil C:N and C:P ratios. And PP runoff loss showed linear and negative correlations with SOC and clay content. Among the six ML models, the XGBoost model achieved the highest predictive accuracy for P runoff loss ($R^2$ = 0.76, RMSE = 0.34, MAE = 0.18) and was thus selected for national simulations. Based on SHAP (SHapley Additive exPlanations) interpretation, precipitation, clay content, soil C:P ratio, P fertilization rate, and soil N:P ratio were identified as key factors influencing P runoff loss at the national scale. This suggests that, beyond hydrological drivers, soil texture, and P input, biogeochemical processes (e.g., mineralization, adsorption-desorption, microbial immobilization) are also critical for P runoff loss. The XGBoost-based national simulations indicated that the average TP runoff loss intensity from Chinese rice cropping systems was 0.77 ± 0.35 kg P $ha^{-1}$ $yr^{-1}$, corresponding to an annual total loss load of 26.61 ± 1.67 Gg nationally. DP and PP contributed approximately 49% and 51% to the TP runoff loss, respectively. The higher TP loss observed in the rice-growing region between the Yellow River and the Yangtze River (e.g., North China single-rice cropping zone (IV)) and lower loss in mountainous southwestern areas (e.g., Southwestern plateau single- and double-rice cropping zone (III)). Spatially, DP runoff loss was the dominant P fraction in southern and northeastern rice-growing regions, whereas PP dominated in central and eastern rice-growing areas. Analysis of zonal dominant factors for P runoff loss revealed that precipitation was the primary controlling factor in the South China double-rice cropping zone (I), the Central China double- and single-rice cropping zone (II), and the Southwestern plateau zone (III). Soil pH emerged as the dominant factor in the North China single-rice zone (IV) and the Northwest China dry single-rice cropping zone (VI). TSN was identified as the key factor in the Northeast early maturing single-rice cropping zone (V). These pronounced regional disparities of dominant factors among the six major rice-growing zones underscore the necessity for implementing region-specific mitigation strategies for P runoff losses. Thus, this study provides critical insights for the precise assessment agricultural non-point source P pollution, and guiding the practices of efficient P nutrient management in the China and other similar agricultural regions worldwide.

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# Influence of Soil Microstructure on Capillary Rise in Disturbed and Undisturbed Sandy Arid Soils, Oman

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**ABSTRACT**

This study investigates the influence of soil microstructure on capillary rise in sandy soils through experiments conducted in arid dunes, Muscat, Oman. While many previous studies have utilized disturbed samples and treated sandy soils as homogeneous, non-stratified media, this research compares both disturbed and undisturbed samples using direct column tests and indirect methods, including empirical equations and the HYDRUS-1D model (a numerical simulation software for modeling water flow in variably saturated porous media) (Šimůnek et al., 2013). Although the samples exhibited similar soil textures, they differed in particle size distribution, saturated hydraulic conductivity (the rate at which water moves through saturated soil), and capillary behavior (the upward movement of water through soil pores against gravity). Notably, the undisturbed sample exhibited lower capillary rise (60 cm) compared to the disturbed sample (73.5 cm), likely attributable to the complex internal structure of dunes, including stratified sand layers (Al Shukaili, 2018), which obstruct water movement as coarser particles in the upper layers act as a capillary barrier. Theoretical models demonstrated varying accuracy, with some models aligning more closely with the sample data. The findings underscore the significant role of soil microstructure in water movement and emphasize the importance of preserving undisturbed soil conditions for accurate assessments in geotechnical and environmental applications.

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# Tracing Water Use Sources in Rubber Monoculture and Rubber-Alpinia Oxyphylla Agroforestry Systems Using Hydrogen and Oxygen Isotopes

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**ABSTRACT**

Global climate change is intensifying the imbalance between water supply and demand. Large-scale monoculture rubber plantations in tropical regions have profoundly impacted regional hydrological cycles and soil moisture balance. While rubber agroforestry systems hold potential advantages, their water utilization sources remain poorly understood. This study focuses on monoculture rubber plantations and rubber-*alpinia oxyphylla* agroforestry systems. Based on isotopic data of atmospheric precipitation, soil water, and plant water from 2021 to 2023, along with their monthly and seasonal variation patterns, we quantitatively analyzed the water sources of the two cultivation modes during wet and dry seasons using the IsoSource and MixSIAR models. The results indicate that the isotopic values (δD and $\delta^{18}O$) of atmospheric precipitation were generally enriched during the dry season and gradually depleted during the wet season, with a significant linear relationship observed between δD and $\delta^{18}O$. Soil water content in monoculture rubber systems (XD) was generally higher than that in the agroforestry system (XY), and significant correlations were observed between δD and $\delta^{18}O$ in soil water under both cultivation modes. In both systems, the $\delta^{18}O$ values of rubber trees intersected with the $\delta^{18}O$ curves of soil water at multiple depths, while fewer intersections were observed for *alpinia oxyphylla*. Plants absorbed a higher proportion of shallow soil water during the wet season, while they relied more on intermediate and deep soil water during the dry season. A comparison of the results from the IsoSource and MixSIAR models revealed that the proportions of water uptake from various potential sources by rubber trees and *alpinia oxyphylla* under different cultivation modes calculated by MixSIAR were lower than those estimated by IsoSource. The findings of this study provide a scientific basis for developing rubber plantation models with rational water-use strategies.

**Keywords:** Hydrogen and oxygen isotopes; Water source; Rubber-*Alpinia oxyphylla* agroforestry system; IsoSource model; MixSIAR model

**Acknowledgments**

This study was supported by the National Natural Science Foundation of China (No. 42167011), the Hainan Province Science and Technology Special Fund (Grant No. ZDYF2024XDNY196), Research Project on Education and Teaching Reform in Higher Education Institutions in Hainan Province (Hnjg2018-11).

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# Effect of dynamic salt precipitation on water and heat transport in unsaturated saline soil: Experiments and simulations

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## ABSTRACT

In arid and semi-arid regions, salt may precipitate as a crust on the soil surface resulting from strong evaporation and shallow saline groundwater, creating a physical barrier that inhibits the evaporative water loss and heat flow to the external environment (Zhang et al., 2014). However, most existing studies on the processes of water and heat transfer under salt crust have focused on saturated or wet soils (Fujimaki et al., 2006; Li and Wang, 2025), and these processes in drying saline soils remain poorly understood. To address this knowledge gap, we employed soil column experiments in a controlled environment with constant radiation to capture the dynamic evolution of salt crust, while improving one-dimensional transient numerical simulations to investigate the influence of salt crust on water and heat transport. The results revealed that salt crust significantly reduced evaporative water loss, with this inhibitory effect being more pronounced in fine-textured soils. However, when the water content dropped below the critical threshold of 26%, salt domes and fissured structures formed on the surface. As a result, a second peak of water loss rate emerged, and water loss in the near-surface soil layer occurred in four stages. Furthermore, salt precipitation reduced net radiation by 29% by increasing albedo, while concurrently increasing thermal conductivity and heat capacity by retaining soil moisture, resulting in lower temperatures and temperature gradients across the profile in saline soil compared to salt-free soil. These thermal behaviors in coarse-textured soils were more dependent on salt precipitation, which can be attributed to increased pore space allowing for the formation of a larger salt crystal continuum. The findings provide new insights for quantifying water consumption, salt accumulation, and surface heat distribution in saline-alkali soils.

**Acknowledgments**

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# Optimizing and Validating a Correction Formula for Xylem Water Deuterium Offsets in Field-Grown Apple Trees

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**ABSTRACT**

Cryogenic Vacuum Extraction (CVE) has become a key method for determining the hydrogen and oxygen isotopic composition of xylem water in plant water source studies due to its advantages of high extraction volume, efficiency, and operational simplicity. However, existing research indicates that isotopic fractionation biases (e.g., deuterium offset) can occur during cryogenic vacuum extraction, leading to distortion of the xylem water isotopic signal and consequently affecting water source apportionment results. Current understanding of deuterium offsets and their correction formulas under real field conditions remains insufficient.

Therefore, unlike previous rehydration-based approaches, this study focused on apple trees – a typical deep-rooted species used in the afforestation of former cropland on the Loess Plateau. Standardized orchard plots with 0%, 20%, and 40% rain-exclusion treatments were established to simulate no-drought, moderate-drought, and severe-drought climatic conditions, thereby obtaining plant samples spanning a wide range of stem water contents. Continuous sampling was conducted throughout the growing season to observe fluctuations in stem water content and deuterium offset. The main conclusions of this study are as follows:

(1) The stem water content gradients set in rehydration experiments could not cover the actual stem water contents observed in the field. In apple trees on the Loess Plateau, stem water content during the growing season ranged from 0.64 to 1.59 g $g^{-1}$, with the highest values occurring in June and the lowest in October.

(2) Compared with existing correction formulas, the optimized formula proposed in this study improved accuracy by 9% and 6%, respectively.

(3) When stem water content exceeded 1.3 g $g^{-1}$, all three formulas demonstrated good correction performance. Within the stem water content range of 0.6–1.3 g $g^{-1}$, both the He formula and the Chen formula exhibited errors, whereas the optimized formula developed here showed errors only when stem water content fell between 0.6 and 0.9 g $g^{-1}$.

In summary, the optimized correction formula presented in this study offers higher accuracy, a broader applicable range of stem water contents, and can be directly applied to correct deuterium offsets in real field samples.

# Transport Pathways of Nitrate in Stormwater Runoff Inferred from High-frequency Sampling and Stable Water Isotopes

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**ABSTRACT**

Storm events can mobilize nitrogen species from landscapes into streams, exacerbating eutrophication and threatening aquatic ecosystems as well as human health. However, the transport pathways and storm responses of different nitrogen forms remain elusive. We used high-frequency chemical and isotopic sampling to partition sources of stormwater runoff and determine transport pathways of multiple nitrogen forms in an agricultural catchment. Bayesian mixing modeling reveals shallow subsurface water as the dominant source of stormwater runoff, contributing 74% of the water flux and 72%, 71%, and 79% of total nitrogen (TN), total dissolved nitrogen (TDN), and nitrate ($NO_3$-N), respectively. Groundwater, by contrast, contributed 11% of stormwater runoff and 21%, 22%, and 17% of TN, TDN, and $NO_3$-N. The remaining 14% of stormwater runoff can be attributed to rainwater, which contains much less TN, TDN and $NO_3$-N. Surprisingly, during storm events the dominant nitrogen form was $NO_3$-N rather than dissolved organic nitrogen. Antecedent conditions and runoff characteristics have an important influence on nitrogen loads during storm events. Our results provide insight into hydrological mechanisms driving nitrogen transport during storm events, and may help in developing catchment management practices for reducing nitrogen pollution in aquatic ecosystems.

**Acknowledgments**

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# Integrated NP Management for Sustainable Soil Fertility and Crop Productivity

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**ABSTRACT**

Integrated Soil Nutrient Management (ISNM) focuses on the judicious integration of organic, inorganic, and biological nutrient sources to sustainably enhance soil fertility and crop productivity. This overview synthesizes findings from a series of field trials conducted across diverse agro-ecological zones, with particular emphasis on the management of nitrogen (N) and phosphorus (P). The trials assessed the combined use of mineral fertilizers with compost, green manures, biofertilizers, biochar, and rock phosphate to evaluate their interactive effects on crop yield, nutrient use efficiency, and soil health indicators. Across locations and seasons, integrated nutrient strategies consistently outperformed sole fertilizer applications by improving nutrient availability, reducing nutrient losses, and sustaining soil organic matter. Overall, the results highlight the effectiveness of ISNM in promoting balanced fertilization, mitigating environmental risks, and strengthening the resilience of farming systems. This synthesis offers valuable guidance for improving nutrient management practices and informing policy initiatives aimed at sustainable agricultural development.

**Key Words:** Integrated Nutrient Management, Nitrogen, Phosphorus, Nutrient Use Efficiency, Soil Health

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# Enhancing Wheat Drought Resilience through Organic Amendments: Integrating Soil Health Improvement and Antioxidant Defense Activation

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**ABSTRACT**

Water stress poses an escalating threat to wheat (*Triticum aestivum* L.), often inducing oxidative damage in plants and deteriorating soil properties. While organic amendments can mitigate these effects, their comparative efficacy in enhancing drought resilience remains insufficiently explored. A pot experiment was conducted using a completely randomized design under a factorial arrangement (two factors) with three replicates. We evaluated four amendments including farmyard manure, organic waste compost, vermicompost, and biochar under three soil moisture regimes (50%, 75%, and 100% field capacity). Severe water stress (50% FC) significantly reduced soil moisture, root growth, nutrient uptake, and yield. Vermicompost combined with 100% FC emerged as the most effective amendment, enhancing drought resilience through a dual mechanism: it acted as a biostimulant, strengthening the plant's antioxidant defense system to reduce oxidative stress, and as a soil conditioner, improving soil organic matter, water contents and aggerate stability. This synergistic enhancement in soil-plant interaction led to better root growth, nutrient uptake, and yield stability under water stress. Our findings highlight the potential of vermicompost as a promising amendment for developing more drought-resilient wheat cultivation systems, a premise that warrants further validation under field conditions.

**Acknowledgments**

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# Degradation of Sugar Beet Pulp by Klebsiella sp. HDJT1 and Pseudomonas sp. C27: A Metabolic Cross-Feeding Strategy for Soil Health Improvement

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**ABSTRACT**

Sugar beet pulp (SBP), a lignocellulosic agricultural waste, holds great potential for bioconversion, but its efficient degradation remains challenging. Our current study investigated the synergistic mechanism of *Klebsiella* sp. HDJT1 and *Pseudomonas* sp. C27 in SBP degradation, focusing on metabolic cross-feeding and quorum sensing (QS) to enhance hydrolysis efficiency and soil-plant-microbe interactions. HDJT1 and C27 exhibit complementary enzymatic profiles: HDJT1 dominated in β-glucosidase activity (11.45 $U \cdot mL^{-1}$), while C27 produced higher endo-β-glucanase (79.43 $U \cdot mL^{-1}$). Their co-culture achieved a 44.05% SBP weight loss in 7 days, outperforming single strains by 13.15–19.60%. C27 recruited diverse microbial communities via QS signaling, optimizing nitrogen (78.4% higher alkaline-hydrolyzable N) and phosphorus cycling core genes such as *phoB* and *phoR*. Meanwhile HDJT1 enhanced cellulose/lignin hydrolysis, reducing lignocellulosic residues to 16.5% after 23 days of in-field degradation. Metabolic cross-feeding between strains enriched rare taxa (e.g., *Pelotalea*, *Desulfovibrio*) and balances N/P cycling, enhancing soil health. This dual-role system (C27 as "ecosystem engineer" and HDJT1 as "metabolic optimizer") advances sustainable agricultural waste management, offering a scalable model for soil fertility improvement through organic waste valorization. Small-molecule carbohydrates released by in-situ degradation of lignocellulose in soil can be used as potential "signal molecules" for underground microbial communication and play an important role in plant-soil feedback.

**Keywords:**
Lignocellulose hydrolysis; metabolic cross-feeding; quorum sensing; soil health; sugar beet pulp.

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# Optimizing nutrient balance in livestock waste to enhance soil organic fertilization and reduce environmental losses

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**ABSTRACT**

The use of livestock-derived fertilizers in agriculture presents significant agronomic and environmental advantages, like enhancing soil organic matter and decreasing dependence on synthetic mineral fertilizers. However, these organic fertilizers frequently exhibit nutrient imbalances that fail to match crop nutritional requirements, often leading to nutrient surpluses and substantial risks of nitrogen (N) and phosphorus (P) losses to the environment. Such losses, through nitrate leaching, ammonia ($NH_3$) volatilization, nitrous oxide ($N_2O$) emissions, and P runoff, pose major sustainability concerns. This research aims at mitigating nutrient losses from agricultural soils by improving the nutrient balance of livestock-based fertilizers, thereby achieving better alignment between nutrient availability and crop uptake.

In livestock-intensive regions, cattle manure is commonly processed through anaerobic digestion for biogas production. The resulting digestate is usually separated into a N-rich liquid fraction and a P-rich solid fraction, generating a nutrient distribution that poorly corresponds to crop needs. Herein, cattle slurry was pre-treated using hydrodynamic cavitation coupled with enzymatic hydrolysis (employing phytase and a mixture of cellulase, hemicellulase, and pectinase) before anaerobic digestion. This process allowed to increase biogas yield while promoting P solubilization and its transfer from the solid to the liquid phase. Consequently, ammonium and phosphate were effectively recovered from the digestate liquid fraction in form of struvite, a slow-release fertilizer, while the N:P ratio of the solid fraction improved from 6.4 to 9.6, better matching with plant nutrient demands.

The resulting materials were tested on A-horizon soils from two Regosols with comparable low N and P contents but differing in texture and pH. A greenhouse experiment with *Lolium multiflorum* Lam compared conventional fertilization with partial or full substitution by pre-treated and untreated digestate solid fractions and recovered struvite. All treatments efficiently supported plant growth while substantially reducing N losses and P runoff as a function of texture and soil pH. This approach can therefore have strong potential to mitigate nutrient losses from soils, while reducing our dependance on synthetic fertilizers. The study also highlights how soil properties can influence the effectiveness of pollution mitigation using bio-based fertilizers.

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# Nutrient Management Effects on Sustainable Yield, Soil Fertility, and Carbon Stock in a Cauliflower–Capsicum Cropping Sequence of the Northwestern Himalayan Region

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**ABSTRACT**

Continuous addition of inorganic fertilizer and farm yard manure (FYM) alone or in combination is necessary to assess the changes in yield and soil properties. Therefore, a study was conducted at the experimental farm of Department of Soil Science and Water Management, Dr. Y. S. Parmar University of Horticulture and Forestry Nauni, Solan (HP) for consecutive two years (2019-2021) to access the effect of nutrient management on sustainable yield, soil fertility, and carbon stock in a Cauliflower–Capsicum cropping sequence of the northwestern Himalayan region. The experiment was laid out in Randomized Block Design having crops *in rabi* and *Kharif* season comprises of nine treatments viz. $T_1$- control, $T_2$-100% FYM (N equivalent basis), $T_3$-100% N, $T_4$-100% NP, $T_5$-100% NK, $T_6$-100% PK, $T_7$-100% NPK, $T_8$-100% NPK+ FYM (recommended Practice) and T9- 150% NPK+ FYM. Results showed that the addition of farm yard manure alone or in a combination with chemical fertilizers contributed to higher soil organic stock and soil carbon sequestration rate. The highest maximum water holding capacity (MWHC) and mean weighted diameter (MWD) were recorded under $T_9$ (47.5 % and 1.39 mm, respectively) and lowest were under control (41.0 %) and $T_3$ (0.66 mm), respectively. The maximum saturated hydraulic conductivity was recorded with treatment $T_2$ (10.6 cm $hr^{-1}$) and minimum was under control (5.9 cm $hr^{-1}$). The maximum CEC was recorded under $T_2$ (14.82 cmol ($p^+$) $kg^{-1}$), whereas minimum was recorded under control (10.49 cmol($p^+$) $kg^{-1}$). Treatment $T_9$ was recorded with highest SOC content (15.2 g $kg^{-1}$), available N (380.5 kg $ha^{-1}$), available P (133.3 kg $ha^{-1}$) and available K (557.7 kg $ha^{-1}$) and the respective parameters were lowest under control (11.7 g $kg^{-1}$, 314.8 kg $ha^{-1}$, 82.9 kg $ha^{-1}$, 453.5 kg $ha^{-1}$), respectively. Application of 150% NPK + FYM improved the SYI of system by 49.4% over a control. This treatment increases soil carbon stock by 12.5% from 25.9 Mg ha−1 to 29.6 Mg ha−1 and recorded with maximum soil carbon sequestration rate, i.e. 2.21 Mg C m−3 year−1 over the 2 years. Thus, balanced fertilization of NPK and FYM is beneficial for the maintenance of soil physical health, improving CEC and macro and micronutrient levels.

**Keywords:** Crop yield, Soil Carbon Sequestration, Sustainability

**Acknowledgments**

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# Conservation Agriculture Impacts Soil Organic Carbon Sequestration, GHG reduction and Sustainable Crop Production

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**ABSTRACT**

Agriculture is the mainstay of Bangladesh's economy, accounting 11.6% of GDP where the crops sub-sector contributes 7.25%. Recently Bangladesh has paid good attention to bio-farming aiming at achieving food security including safe and nutritious food while minimizing environmental degradation. This approach discourages use of chemical fertilizers & pesticides and instead encourages the use of organic and bio-fertilizers. Organic fertilizer (e.g., compost, vermi-compost, tricho-compost, biochar) use is especially important to produce fruits and vegetables. Conservation agriculture (CA) in this country is an emerging sustainable approach which helps soil organic carbon sequestration, GHG reduction, and decreased cost of production (fuel, labor & irrigation).

We had a 20-year study until recent on CA practice which encompasses minimal soil disturbance (zero tillage, strip tillage, bed planting), crop residue retention and legume-based crop rotation. This practice (CA) is found more suitable for dryland crops like wheat, mustard & pulses and less for wetland rice. It contributes to C stock in soil at a rate of 0.5-1 t $ha^{-1}$ $yr^{-1}$ depending on the duration of CA practice, amount of residue retention and crop diversification. CA shows 24.5% less carbon footprint and 28.5% less emission intensity or global warming potential than conventional practice. Reduced or zero tillage reduces the mixing of crop residues in the soil thereby resulting in lower decomposition rates and $CO_2$ emissions.

It was observed that bed planting improved seed placement, reduced irrigation needs and increased yields by 15–20% for mustard, wheat, and maize. Strip tillage (ST) in mustard, lentil, and potato cultivation demonstrated good economic returns, better yields, and significantly reduced fuel use and thus $CO_2$ emissions. For example, mustard (var. BARI Sarisha-17) under ST yielded 1.77 t/ha with 66% lower $CO_2$ emissions than the broadcast method of sowing. Zero tillage trials in coastal and lowland areas showed higher crop yields, lower labor and fuel cost, reduced salinity effects, and improved soil health through mulching.

Conservation agriculture is a sustainable farming practice that influences soil organic carbon sequestration, reduces GHG emissions and produces sustainable crop yield.

**Keywords:** Conservation agriculture, Carbon sequestration, GHG emission, strip tillage, profitable crop yield.

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# Short-term interaction between earthworms, compost and biochar on GHG emissions and N mineralization

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## ABSTRACT

Earthworms enhance compost mineralization, improving its fertilizer value and soil quality (biological activity, structure). However, they often increase greenhouse gas (GHG) emissions, particularly nitrous oxide ($N_2O$), via nitrogen mineralization. Combining biochar with compost may mitigate these emissions while further boosting soil benefits alongside earthworm activity. We present preliminary results from a soil incubation (2 months) experiment testing this synergy. Using a Norwegian loam Cambisol, a 2x2x2 factorial design (four replicates) assessed the presence/absence of earthworms (Lumbricus terrestris - 10 adults/jar), compost (manure/food waste - 60 Mg $ha^{-1}$ equivalent), and rice-straw biochar (700°C pyrolyzed - 20 Mg $ha^{-1}$ equivalent). We hypothesized that earthworm and compost addition may present synergistic effects in improving N mineralization with consequent enhanced GHG emissions. We expect that biochar may counteract these emissions and potentially present positive effects for soil quality. The goal was to develop a biochar-compost-earthworm system creating a fertilizer with higher nutrient availability and lower GHG emissions. In the first week of the incubation, we found that higher $CO_2$ and $N_2O$ productions were associated with the presence of compost. Earthworms could further enhance the carbon decomposition but appeared to mitigate CH4 production. Further analysis will be carried out with a focus on GHG emissions ($CO_2$, $CH_4$, $N_2O$) and nitrogen mineralization dynamics.

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# Bacillus megaterium (S2-4a1) Improves Compost Biofertilizers by Solubilizing Potassium from Feldspar

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**ABSTRACT**

The rising cost of synthetic fertilizers coupled with their adverse effects on the soil led to the emergence of biofertilizers as sustainable alternatives. However, the low potassium (K) content of compost biofertilizers often fails to meet the demand of crops. Meanwhile, K-rich minerals, such as feldspar, are underutilized, due to their relative recalcitrance. Against this backdrop, K-solubilizing bacteria are being utilized to mobilize mineral K from such sources. However, a research gap exists regarding using PSB to release K from feldspar and hence improve compost biofertilizers. This study aimed to bridge that gap by using *Bacillus megaterium* S2-4a1 to solubilize potassium in compost-feldspar mixtures. A Completely Randomized Design (CRD) comprising five treatments (T1 — compost control; T2 — compost + *B. megaterium*; T3 to T5: compost + *B. megaterium* + feldspar + rock phosphate at rates of 2.5, 5.0 and 10.0g, respectively) of three replicates each was used to quantify how *B. megaterium* (S2-4a1) solubilizes total and exchangeable potassium in a feldspar-compost biofertilizer mixture during a 60-day incubation period. The results indicated that *B. megaterium* treatments produced higher total and exchangeable K ($p < 0.01$ and $p = 0.0004$, respectively) than the compost control. Meanwhile, the highest exchangeable K was observed in T5 at 15 and 60 days (0.2559% and 0.3082%, respectively), however, these values were not significantly different from those of the T4 treatment (0.2543% and 0.2851%, respectively). On the whole, combining *B. megaterium* S2-4a1 with moderate amount of feldspar (5g) appears to be the most cost-effective treatment for substantially enhancing exchangeable K to improve compost biofertilizers within 15 days. Further studies to elucidate the K-solubilization mechanisms and optimize substrate:inoculum ratios are necessary before devising scalable field strategies employing this K-solubilzing bacterium to mobilize K from feldspar and other minerals towards enhanced soil and agricultural sustainability.

**Acknowledgments**

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# Innovative Nutrient Recycling through Black Soldier Fly (Hermetia illucens) Rearing: Comparison of three Organic Waste Substrates—Food Waste, Bread, and their Mixture.

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**ABSTRACT**

Optimized management of organic waste is essential to limit resource losses and reduce greenhouse gas emissions. The present study evaluated the efficiency of organic waste valorisation through insect farming, especially *Hermetia illucens* (black soldier fly) larvae, feed with three distinct feedstocks: food waste, bread, and a mixture of the two (70%+30%, respectively).

The results show that the mixed substrate promotes optimal larval growth, high efficiency in converting waste into biomass, and a balanced larval composition in terms of protein and lipid content. The frass derived from the mixed substrate also exhibited interesting properties for use as a soil amendment and fertilizer, particularly in terms of total nitrogen and sulfur contents. Conversely, frass obtained solely from food waste shows superior characteristics in terms of potassium, total calcium, and micronutrients — specifically Fe, Zn, Mn, and Cu — compared to the other two feedstocks.

Frass pH measurements indicate that the food waste substrate generates a significantly higher pH (around 7.2), followed by the bread substrate, while the frass from the mixed substrate presents a lower pH (~ 6.2). Regarding electrical conductivity (EC), the frass from food waste showed the lowest value, suggesting low accumulation of soluble salts, whereas no significant difference was observed between the bread and mixed substrates, both showing higher EC values (~ 10 ms/cm), almost double that of food waste.

We have also conducted a phytotoxicity test (germination test) using rye grass seeds treated with different concentration of frass extracts (0, 20%, 60% and 100%). We found that all frass-based treatments enabled the germination of ryegrass, with varying germination indices depending on the concentration applied and the type of frass used. At a 20% concentration, frass derived from the bread and food waste substrates showed germination indices above 100%, indicating potential phytostimulant activity. In contrast, frass from the mixed substrate exhibited, at the same concentration, a slightly lower germination index (around 60%), suggesting moderate phytotoxicity. At higher concentrations (60% and 100%), frass from the bread and mixed substrates showed indices below 60%, indicating high phytotoxicity. The frass obtained from the food waste substrate, however, showed no notable phytotoxicity at 60% concentration and only moderate phytotoxicity at the maximum concentration of 100%.

Principal Component Analysis (PCA) clearly reveals distinct profiles depending on the substrate used, highlighting the major impact of waste type on the nutritional and agronomic quality of the products obtained from larval composting. This work thus confirms the relevance of the black soldier fly as an attractive and innovative solution for sustainable organic waste management within a circular economy model, with significant implications for improving soil fertility and health.

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# Clay-stabilised Composts to Enhance Soil Health and Carbon Storage in Sandy Soils.

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## ABSTRACT

Enhancing soil organic carbon (C) sequestration is critical for improving soil health and mitigating climate change. This study explores an innovative strategy of co-composting clay materials with food waste to enhance organic C stability and reduce $CO_2$ emissions in soil. Bentonite (B) and kaolinite (K) clays were co-composted with food waste (FW), followed by a soil incubation experiment under controlled conditions. Treatments included unamended compost (FW0), bentonite-amended compost (FWB), and kaolinite-amended compost (FWK).

Results showed that clay amendments significantly reduced dissolved organic carbon (DOC) in the soil. FW0 resulted in the highest DOC, which declined in FWB and FWK after 56 days of incubation, confirming enhanced C stabilisation in clay-amended treatments. Microbial biomass carbon (MBC) was higher in FWB (~2200 mg C $kg^{-1}$) and FWK (~1350 mg C $kg^{-1}$) compared to FW0 (~750 mg C $kg^{-1}$), indicating improved microbial activity in clay-amended soils. $CO_2$ respiration rates were lower in FWB and FWK (150-160 µg $CO_2$-C $kg^{-1}$ $day^{-1}$) compared to FW0 (~207 µg $CO_2$-C $kg^{-1}$ $day^{-1}$), reflecting reduced microbial decomposition and enhanced C protection in clay-amended soils. Clay amendments also influenced nitrogen dynamics; $NH_4^+$ concentrations were elevated in soils amended with FWB and FWK, indicative of enhanced nutrient mineralisation and retention. However, $NO_3^-$ levels were not significantly influenced by clay type, highlighting a stronger influence of clay on $NH_4^+$ stability rather than $NO_3^-$ production. Soil pH was positively affected, with clay amendments (particularly FWB) increasing pH (7-8) compared to the consistently acidic FW0 treatment (4-5), suggesting improved conditions for microbial activity and nutrient availability.

Overall, clay incorporation in composts significantly enhances organic C stability by reducing DOC lability, elevating $NH_4^+$ availability, and improving soil chemical conditions, thus creating a favourable environment for microbial activity. These findings confirm the potential of clay in co-composts as effective amendments for long-term carbon sequestration, improved nutrient dynamics, and sustainable soil management.

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# Straw return facilitates the availability of soil nitrogen by altering the metabolic distribution and nitrogen cycling processes

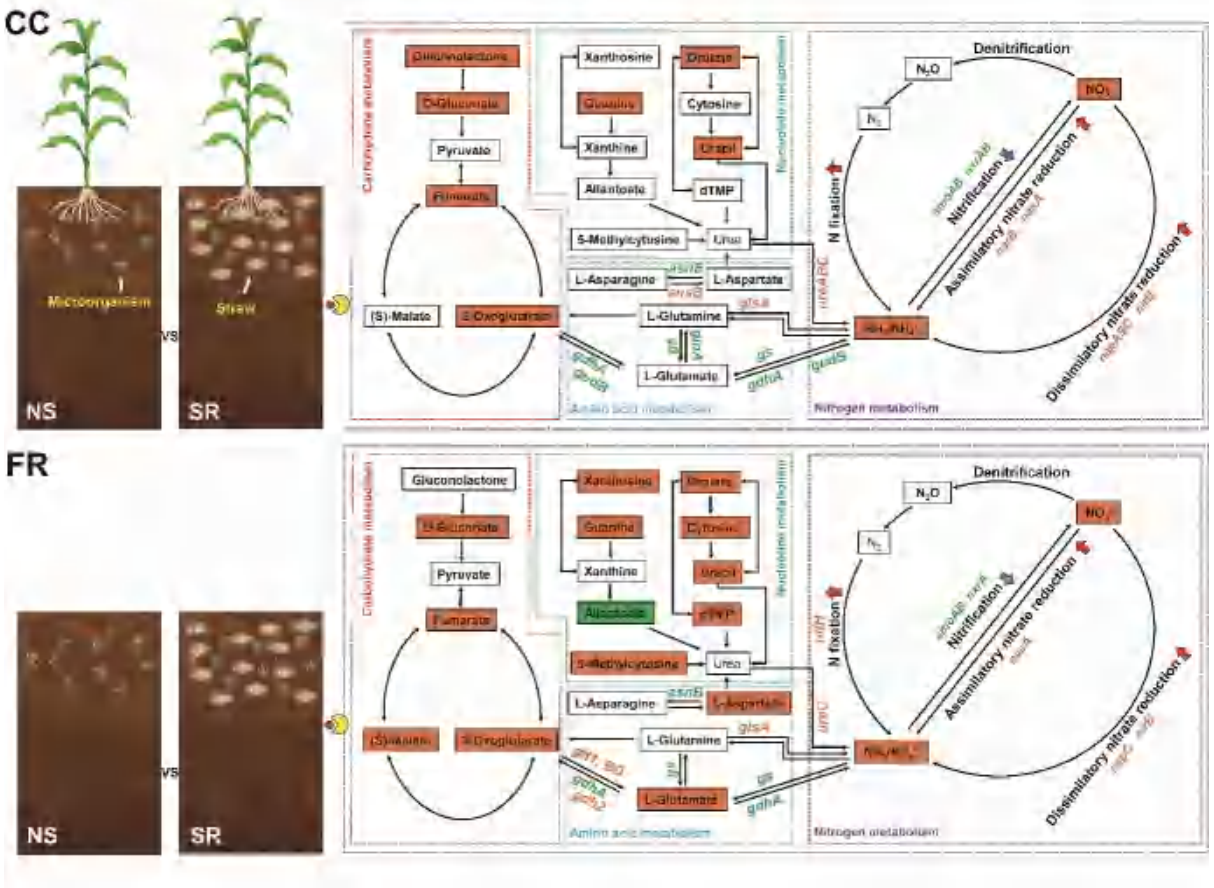
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## ABSTRACT

Straw return (SR) has been extensively utilized to enhance soil organic carbon (SOC) levels and soil fertility in agroecosystems. However, the impact of SR on soil nitrogen (N) dynamics, microbial communities, metabolic processes, and the underlying mechanisms remains largely unexplored. Through a multi-year manipulation of SR under continuous corn cropping (CC) and fallow (FR), we demonstrate that SR promotes N availability by altering soil microbial metabolism. Moreover, SR facilitated N turnover by enhancing metabolic pathways, including arginine biosynthesis, alanine, aspartate, and glutamate metabolism, as well as glycine, serine, and threonine metabolism, and pyrimidine and purine metabolism. Additionally, SR resulted in a significant increase in the abundance of microorganisms and functional genes involved in mineralization (*glsA* and *ureC*), N fixation (*Bradyrhizobium*, *Altererythrobacter*), dissimilatory nitrate reduction to ammonium (DNRA, *Sorangium*, *napC*, and *nirB*), and assimilatory nitrate reduction to ammonium (ANRA, *nasA*). However, despite a reduction in the relative abundance of nitrification microbes and functional genes (e.g., *Nitrososphaerag*, *Nitrospira*, *Sphingomonas*, *amoAB*, *nxrA*), SR enhanced the content of extractable inorganic N and organic N in the soil. Therefore, SR represents an effective strategy to promote N dynamics and accelerate the restoration of soil fertility. Our results demonstrated that SR alters N cycling processes by modifying microbial community structure and metabolite distribution, thereby increasing soil N availability.



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# Effects of straw incorporation on soil carbon and nitrogen sequestration in fallow and continuous maize cropping systems in Northeast China

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**ABSTRACT**

Straw incorporation (SI) increased soil organic carbon (SOC) and total nitrogen (STN). However, the differences in soil responses between maize cropping system and fallow management system under different SI rates in the black soil region of Northeast China remain unclear. In a 6-year experiment, we examined these two systems by using round frames with five annual SI rates (0, 9.2, 18.4, 27.6, and 36.8 Mg $ha^{-1}$) to investigate their effects on soil C and N fractions and storage potential. SI significantly enhanced the SOC and STN concentrations in both maize cropping system and fallow management system. Compared to fallow, continuous maize cropping resulted in higher depletion of oxidizable organic C (EOC) and amino sugar N (ASN) but maintained greater light fraction organic C (LFOC), particle organic C (POC), and hydrolysable unknown N (HUN) concentrations in the 0-15 cm soil layer. Fallow increased the soil C:N ratio and exhibited higher average annual C and N sequestration rates (0.70 and 0.01 Mg $ha^{-1}$ $yr^{-1}$, respectively) compared to the maize cropping system. However, increasing SI rates did not significantly affect the transformation efficiency of straw-derived nutrients. Conventional SI rates in continuous maize cultivation led to soil C and N losses, while higher SI rates and fallow management effectively retained nutrients. Thus, to prevent concurrent losses of soil C and N pools under continuous maize cropping with current soil conditions in the 0-30 cm layer, an annual input of at least 6.8 Mg C $ha^{-1}$ $yr^{-1}$ and 0.2 Mg N $ha^{-1}$ $yr^{-1}$ is recommended.

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# Differences in soil organic carbon accumulation caused by microbial-mediated tillage and carbon input

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**ABSTRACT**

Tillage and C input are considered to be important management measures to maintain the sustainable production capacity of farmland soil. However, the understanding of the further binding of fungal necromass carbon ( FNC ) and bacterial necromass carbon ( BNC ) to SOC fractions between soil layers is still limited. Therefore, we arranged the same tillage and carbon input treatments in four farmlands in Jilin Province, China, to analyze the difference and mechanism of microbial necromass carbon ( MNC ) to SOC sequestration between topsoil ( 0-20 cm ) and subsoil ( 20-40 cm ). In the topsoil, the increase of carbon input promoted the increase of soil nitrogen content and enzyme activities, and the microbial biomass carbon increased significantly, which promoted the accumulation of FNC and BNC. FNC directly promoted the formation of MAOC, and fungal and BNC together increased POC.The distribution of microorganisms to organic carbon components increased the proportion of POC in SOC, but MAOC still dominated, and SOC content increased by 5.6%, which was not limited by tillage. Different from topsoil, although tillage and carbon input reduced enzyme activity in the subsoil, due to tillage promoted the activity of bacteria such as Proteobacteria and Actinobacteriota and the synergistic decomposition and reuse of enzymes, the FNC content decreased with the increase of C input, resulting in the decrease of POC content dominated by C input. At the same time, the ability of residual carbon to bind to MAOC is weakened due to environmental changes. As a result, SOC decreases with the increase of C input after additional C input. These findings suggest that carbon sequestration in the whole tillage layer is not entirely dependent on C input, but through the comprehensive regulation of tillage, straw and organic fertilizer, higher carbon sequestration benefits of farmland soil can be obtained.

**Keywords:** Carbon input;Carbon sequestration;Microbial necromass carbon;Microbe-mediation

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# Applying a combination of artificial humic acid and microbial agent to increase rhizosphere soil organic carbon content and maize yield

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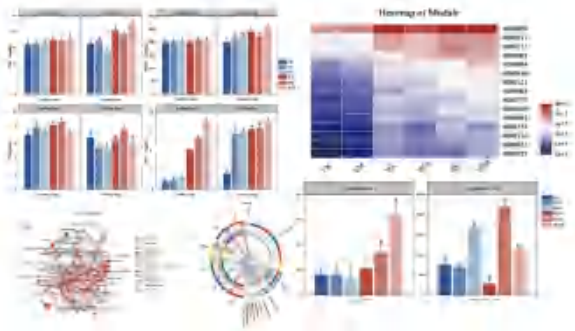
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**ABSTRACT**

Biostimulants, including artificial humic acid (A-HA) and microbial inoculants, are gaining attention for enhancing soil fertility and crop growth. This study explores their combined effects on rhizosphere soil organic carbon (SOC) fractions and microbial activity. In this investigation a pot experiment of maize was carried out with six treatments, including the synergistic or independent action of artificial humic acid and microbial agents, and a control. Then soil at various growth stages were collected to determine organic carbon, enzyme activity, microorganism community structure, and the growth of the maize, which has been calculated and analysed by high throughput sequencing, principal component analysis and Shannon index to evaluate the effects of different treatments. A-HA at 200 mg/kg enhances the availability of nutrients, enzyme activity, root development and favors superior growth, better yielding capacity and increasing stability of soil carbon with microbial agents. It increases soil humification, decreases the activity of enzymes for carbon turnover at 400 mg/kg, decreases gene abundance for metabolism of nutrients, increases gene abundance for carbon fixing microbes and gene abundance of stable pathway of carbon so as to increase the active organic carbon to stable organic carbon and elevate the content of overall soil organic matter. The combined application of A-HA and microbial inoculants significantly enhanced SOC fractions and soil nutrient conditions, while stabilizing microbial community abundance in the rhizosphere. This study provides theoretical guidance for improving crop yield through practical application of these soil amendments.

**Keywords:** Artificial humic acid; Rhizosphere soil; Enzyme activities; Microbial community; Soil fertility



A-HA and microbial consortia can both evidently enhance maize growth and finally improved the mature stage yield by changing soil labile organic carbon fractions, soil nutrients and leaf photosynthesis. The results showed that the addition of A-HA and microbial agents as biostimulants in the $H_2M$ treatment group enhanced a signifi- cantly (40.49%) the level of TOC, (19.77%) the level of MBC, and (331.72%) the level of DOC than the control group. As for the content of soil nutrienst, the HM treatment group showed the greatest total nitrogen (13.81%), available phosphorus (11.25%), and available potassium (16.00%), respectively, compared to the control. Additionally, The use of A-HA and microbial consortia as biostimulants which stimulated the multiplication of bacteria with functions on soil carbon cycling, and mineralization, The result showed that, the abundance of *Gemmatimonas* bacteria was highly promoted by the $H_2M$ treatment during the maize plant jointing stage, where increased its abundance by 290.94% compared to (CK). While in the HM treatment it increased by 194.37% compared to (CK), suggesting an activation to a specific bacterial subgroup with particular traits to enhance plant performance and production. Maize Yield: The higher yield at maturity was of 28.00% (indirectly) linked to an increase of Escherichia coli abundance by 41.90%.

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# Nutrients Leaching In a Maize Stover Biochar Amended Soil

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**ABSTRACT**

Agricultural productivity is severely impeded by soil nutrient leaching, especially in tropical areas like Ado-Ekiti, Nigeria, where intense rainfall promotes nutrient loss. Soil nutrient leaching is a significant environmental and agronomic issue that impacts soil fertility, water quality, and crop yield. This study evaluate the effect of maize stover biochar (MSB) rate on selected macronutrient leaching and investigate the short-term potential impact of MSB on the soil from the Ekiti State University Teaching and Research Farm, Ado-Ekiti (EKSU-TRF), Nigeria. Pyrolyzed MSB was produced at an average of 460 °C and a leaching column experiment was conducted using soil amended with MSB at rates of 0, 2, 4, and 6 ton $ha^{-1}$, simulating rainfall over 90 days. The leachate collected and the soils sampled (before and after the experiment) were analysed to determine the pH, electrical conductivity (EC), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) contents. Result shows that MSB application significantly increased leachate volume, with the highest volume recorded at 6 ton $ha^{-1}$, indicating improved soil porosity and drainage. Leachate analysis revealed elevated pH (7.45-9.41), EC (0.005-0.283 *d*S $m^{-1}$), P (5.09-81.05mg $l^{-1}$), K (107.84-6348.04 mg $l^{-1}$) and Mg (62.50-135.00 mg $l^{-1}$) concentrations, with P and K leaching peaking at 60 days. The leachate volume for Ca reduced with MSB rates. Post-experiment soil analysis shows increased pH (6.20-8.35), EC (0.060-3.090 *d*S $m^{-1}$), total organic carbon (0.49-0.97 g $kg^{-1}$), total N (0.03-0.15 g $kg^{-1}$), available P (4.14-34.40 mg $kg^{-1}$), exchangeable K (0.10-1.89 cmol $kg^{-1}$), Ca (0.85-0.93 cmol $kg^{-1}$), Mg (0.34-0.87 cmol $kg^{-1}$) and water retention (1.99-16.08%) with increasing MSB rates. The MSB improved soil fertility, however, higher application rates increased nutrient leaching risks due to the soil's sandy texture. Long term biochar application on various soil types and economic feasibility is recommended.

**Keywords:** Maize stover biochar, nutrient leaching, soil fertility, tropical soils, macronutrients

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# Organic management effect on soil characteristics: a comparison between vineyard and field crop rotation

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**ABSTRACT**

This study, conducted in the University of Padova experimental farm, investigates and compares the effects of long-term (20 years) organic management in two different cropping systems (vineyard *vs.* field crop rotation - FCR) on soil copper (Cu) and sulphate ($SO_4^{2-}$) accumulation, soil organic carbon (SOC) content, as well as other nutrients content (TKN, P, K, $NO_3^-$, Ca, Mg, $K_{exc}$, $PO_4^{3-}$, Fe) along the 0-40 cm soil profile. In vineyard, the fungal disease control is performed with the use of Cu and sulfur (S), and reduced tillage and inter-row cover are applied. FCR is based on annual moldboard plowing and sporadically used or not at all applied Cu and S treatments. The soil sampling was carried out in 2023 considering an area of approximately 1 ha for each cropping system. Vineyard showed the highest Cu content in both the 0-20 cm (450 kg $ha^{-1}$) and 20-40 cm (300 kg $ha^{-1}$) soil profiles, compared to both FCR layers, for which the Cu content was on average 120 kg $ha^{-1}$. Vineyard showed surface enrichment for $SO_4^{2-}$, too, while FCR soil accumulated $SO_4^{2-}$ in deeper layers, likely due to increased leaching and plow-induced movements. The surface layer of the vineyard was richer in SOC (44.1 Mg $ha^{-1}$) than the deeper layer and both FCR layers (on average 34.1 Mg $ha^{-1}$). Ca, Mg, and Fe were also higher in the top 20 cm of vineyard soil, whereas FCR accumulated higher $PO_4^{3-}$ and had a more homogeneous nitrogen distribution along the entire soil profile. The study highlighted how the two different organic management strategies can influence Cu buildup over time and the interaction with the main crops' nutrients and highlighted the possible implications for environmental sustainability.

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# Organic Waste Amendments as Drivers of Soil Fertility and Microbial Activity in the Strawberry Rhizosphere

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**ABSTRACT**

This study examines the effects of various organic waste types on the soil properties in the rhizosphere of Albion strawberry plants (*Fragaria x ananassa Duch.*). Eight organic wastes were tested: Cow Manure (CM), Poultry Manure (PM), Sheep Manure (SM), Vermicompost (VC), Rice Husk (RH), Wheat Straw (WS), Tea Waste (TW), and Hazelnut Husk (HH). These were applied before transplanting the strawberries. Conducted in a controlled greenhouse, the research assessed the impact of 5% organic waste on plant growth and soil characteristics, monitoring soil moisture near field capacity over 61 days. Soil samples were analyzed for microbial biomass carbon (MBC), basal soil respiration, and enzyme activities. Results showed that tea waste significantly enhanced basal soil respiration, while wheat straw increased microbial biomass carbon. Sheep manure notably affected dehydrogenase activity, and poultry manure increased catalase activity. All treatments improved soil organic matter, with sheep manure, cow manure, and vermicompost raising nitrogen levels, while others like tea waste and rice husk decreased it. These findings highlight that diverse organic waste can enhance soil health and strawberry growth, providing valuable insights for sustainable farming practices.

**Keywords:** Organic waste, Strawberry, Plant growth, Microbial activity, Sustainable agriculture.

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# Regulation of Aggregate Nutrients and Microbial Processes by Organic Materials Incorporation to Enhance Soil Quality and Crop Yield

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**ABSTRACT**

Soil aggregates serve as functional units within soil ecosystems, playing a pivotal role in nutrient storage and cycling. Long-term application of organic materials (including organic manure and crop straw) has been demonstrated to be an effective approach for improving soil structure, enhancing soil quality, strengthening nutrient sequestration, and ultimately increasing crop yield. Based on multiple long-term field experiments, this study systematically investigates the impact of organic materials incorporation on soil physical, chemical, and microbial properties at the aggregate scale, as well as crop yield. Overall, the application of organic amendments (organic manure: 15–22.5 Mg $ha^{-1}$ $y^{-1}$; straw: 2250–15000 kg $ha^{-1}$ $y^{-1}$) significantly promoted the formation and stability of >250 μm aggregates, meanwhile, pore number of >100 μm, porosity of >2 μm, and morphological characteristics (anisotropy, circularity, connectivity and fractal dimension) significantly increased, but the total number of pores significantly decreased ($P$<0.05). Dissolved organic matter concentration in soil aggregates increased by 11.8%–42.7% in organic materials incorporation treatments, and shifted in composition. Fulvic-like and humic-like components increased and protein components decreased, suggesting a transition towards microbial-derived organic matter, enhancing soil humification and bioavailability. Organic materials incorporation also enhanced the complexity of microbial co-occurrence networks within 2000–250 μm aggregate, and alleviated microbial carbon (by 0.93–2.29%) and phosphorus (by 0.80–2.94%) resource limitations. Further analysis revealed organic materials incorporation increased soil quality index in topsoil and subsoil by 18.32%–33.08% and 2.43%–16.99%, respectively. 2000–250 μm aggregates within topsoil and >2000 μm aggregates within the subsoil contributed the most to the soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) storage. The TP content within >2000 μm aggregates was an important predictor influencing soil carbon, nitrogen, and phosphorus stocks. Nitrogen and phosphorus stocks were important predictors influencing soil quality. Consequently, organic amendment incorporation improved the soil quality index by enhancing aggregate structure, chemical properties, and microbial activity, thereby promoting increased crop yield, with aggregates >250 μm primarily influencing this process. These findings provide valuable insights for understanding soil quality improvement at the aggregate scale and exploring effective field management strategies.

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# Soil Biogeochemical Responses to Composting and Organic Waste Application Across Agricultural Systems

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**ABSTRACT**

Municipal solid waste in the United States exceeds 292 million tons annually, with more than one-third consisting of organic materials such as food and green waste. Yet only ~20 percent of these materials are composted, and most still enter landfills, where they contribute substantially to methane emissions and generate leachates and volatile organic compounds. As state-level restrictions on landfilling organic waste expand, there is growing interest in management strategies that both improve soil function and reduce environmental impacts. However, key uncertainties remain regarding how composting and direct land application of uncomposted organic materials influence nitrogen transformations, nitrous oxide ($N_2O$) emissions, and nitrate leaching across diverse soil conditions.

This study integrates field monitoring, laboratory incubations, and $^{15}N$ tracer experiments to evaluate how composting systems, compost amendments, and uncomposted green-waste applications regulate soil biogeochemical processes. Multi-season observations show that managed composting windrows emit both $CH_4$ and $N_2O$, but at substantially lower greenhouse gas intensities compared with landfilling. Seasonal contrasts highlight the central role of oxygen availability: winter piles with limited aeration generated elevated $CH_4$, whereas summer piles under warm, oxygenated conditions produced more $N_2O$. These patterns underscore the importance of moisture control, feedstock porosity, and turning frequency in mitigating emissions during composting.

Across soil textures and compost types, $^{15}N$ tracer experiments demonstrated that compost amendments consistently reduced cumulative $N_2O$ emissions relative to mineral fertilizer, with the proportional contributions of compost-, soil-, and fertilizer-derived N varying by nitrogen form and texture. In contrast, surface application of uncomposted green waste significantly increased $N_2O$ emissions compared with incorporation, despite similar nitrate leaching responses. Laboratory incubations further revealed that green waste accelerates oxygen consumption, altering $N_2O$:$N_2$ ratios and enhancing gaseous nitrogen losses when left at the soil surface.

Together, these findings highlight organic waste as a valuable but under-utilized resource for improving soil carbon and nutrient cycling, while emphasizing management-dependent tradeoffs for greenhouse gas mitigation. Strategically integrating composting with informed application practices—particularly soil incorporation of uncomposted materials and optimized windrow aeration—advances climate-smart soil management and supports a more circular bioeconomy.

# Partial organic substitution enhances ecosystem services in agricultural soils

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## ABSTRACT

Ensuring global food security while minimizing environmental impacts necessitates a transition towards sustainable agricultural practices, such as partially substituting chemical fertilizers with organic amendments. Although numerous studies have documented the effects of partial organic substitution on crop yield, environmental footprints, and microbial community structure, comprehensive assessments of how it influences soil ecosystem multifunctionality and the underlying microbial mechanisms remain limited. Crucially, the temporal dynamics of microbial communities in response to these practices and their role in mediating trade-offs and synergies among ecosystem services are poorly understood.

This study investigated the effects of partial substitution of chemical nitrogen (N) fertilizer with organic amendments in a vegetable production system. Treatments included: zero-nitrogen control, conventional chemical fertilization, and substitutions of 25% or 50% of chemical N with either pig manure or sewage sludge compost. We evaluated impacts on crop yield and quality, soil fertility, greenhouse gas and reactive N (Nr: $NH_3$ volatilization, N leaching and runoff) releases. An economic cost-benefit analysis integrated these aspects to assess overall ecosystem service value.

Key findings revealed that organic substitutions enhanced multiple ecosystem services. It significantly increased vegetable yield by 37.1-47.1% and improved quality, thereby boosting provisioning services. Critically, organic substitutions transformed the system from a carbon source to a sink, enhancing regulating services through a 28.6-43.3% reduction in greenhouse gas emissions and a 19.9-39.8% decrease in Nr losses. Economic analysis demonstrated that despite higher initial input costs, organic substitutions, particularly 50% pig manure, yielded the highest net economic benefit per unit area and yield, largely due to mitigated environmental cost.

The enhanced ecosystem multifunctionality was linked to reshaped soil microbial communities. Organic substitutions significantly increased soil pH, total N, SOC, and extracellular enzyme activities related to C, N, and P cycling. Notably, it elevated the abundance of the $N_2O$-reducing gene more than $N_2O$-producing genes, explaining the reduced $N_2O$ emissions. Microbial communities exhibited significant temporal dynamics, with divergence increasing over time. Ecological network analysis confirmed that organic substitution enhanced the complexity and positive interactions within bacterial-fungal networks. These microbial changes are pivotal mechanisms driving the observed enhancement of soil ecosystem multifunctionality.

This study provided a holistic perspective on recycling organic wastes into agriculture, demonstrating that partial substitution is a strategy capable of synergistically enhance productivity, economic benefits, and environmental performance by fostering a functional and resilient soil microbiome. The research highlights the critical role of managed microbial communities in achieving climate-resilient, circular nutrient economies, aligning with the global need for sustainable soil management.

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# Optimizing management of organic inputs to improve biomass production and nitrogen efficiency in Danish organic cropping systems

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**ABSTRACT**

Organic farming and the use of organic amendments are widely recognized as sustainable strategies to minimize environmental footprints in agricultural production. However, improving nutrient use efficiency and obtaining higher yields remain key challenges in organic cropping systems. To explore the best practices to optimize the management of organic inputs in organic systems, a long-term experiment CROPSYS, was established in Denmark in 1997. The experiment includes three cropping systems growing similar crops: a conventional rotation (CGL) receiving mineral fertilizers including three cereal crops and lupine-barley intercrop as a grain legume, and two organic rotations with either N-fixing grain legume (OGL), or grass-clover as green manure (OGM). The organic systems were with or without the application of digested manure. The three systems were also designed with and without cover crops. Here, we will present the results from the latest 4-year rotation cycle (2019–2022) together with a historical overview, and share the innovative use of grass-clover-based digestate from biogas production as a renewable green manure in Denmark. The results showed that the inclusion of a green manure crop increased the yields of subsequent crops (spring wheat and winter rye) in organic systems, whereas it had a higher risk of nitrate leaching. Cover crops had slight effects on crop yields but significantly reduced nitrate leaching in both organic and conventional systems. To maximize clover's value, it was used to produce bioenergy (biogas), and the digestate was in turn applied to the field as biofertilizer. By exploring the innovative use of plant-based fertilizer, we are optimizing Danish organic cropping systems to improve nutrient use efficiency and narrow the yield gaps compared to conventional systems, while reducing climate impact.

**Acknowledgments**

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# Torrefied biomass (biotorr) as soil amendment: insights from multivariate and temporal analysis

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**ABSTRACT**

Understanding soil-plant nutrient dynamics over time under different management practices is critical for developing sustainable agroecosystems. Torrefied biomass (biotorr), an intermediate thermally treated product between raw straw (RS) and biochar, may combine the advantages of both materials, i.e., stimulate microbial activity while enhancing soil C sequestration. Yet, most studies focus on biochar and RS, and little is known about biotorr effects on plant growth and soil nutrient dynamics. This knowledge gap limits the development of strategies that promote sustainable nutrient management. To address this challenge, we conducted a four-month pot experiment in a greenhouse using Italian ryegrass (*Lolium multiflorum* Lam.) as a test crop. The effects of biotorr on plant growth and nutrient allocation across successive harvests were explored, along with their impacts on soil properties. Treatments included two types of biotorr (230°C and 280°C) and a biochar (400°C), all produced from the same feedstock (rapeseed stalks), as well as RS, mineral fertilizer (NPK), and untreated soil (control). Organic amendments were applied at a rate of 10 t $ha^{-1}$. Plant traits (height, biomass, and shoot concentrations of N, P, and K) were measured and used to calculate nutrient uptake, N use efficiency, and the N/P ratio. Soil properties were assessed at the final harvest and included pH, total N, available P and K, and total organic C concentrations. Multivariate and univariate analyses were applied to capture plant-soil trait interactions and treatment effects. Plant responses were treatment-specific at the first harvest but converged by the final one, with responses more linked to soil chemistry, where soil pH emerged as the most influential factor. Biotorr at 230°C significantly increased soil pH, while biotorr at 280°C enhanced total organic C compared to the control. Both biotorr types and biochar enhanced soil nutrient pools compared with treatments NPK and control. Fertilizer equivalence coefficients indicated biotorr at 230°C and biochar achieved up to 13% and 20% of NPK efficiency in biomass production at maturity, respectively. The results suggested a temporal shift in the drivers of plant-soil nutrient dynamics, implying that strategies targeting nutrient efficiency should prioritize early-season interventions to support growth and late-season adjustments to balance nutrient levels. These findings highlight biotorr's dual role as a complementary amendment to mineral fertilization, enhancing nutrient cycling and improving soil quality.

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# Advancing Soil Fertility Management Using Tuna Meal Organic Waste: Impacts on Rhizosphere Microenvironment and Tea Quality

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## ABSTRACT

Tea (*Camellia sinensis*) is a typical leaf-harvested economic crop, its growth and quality are largely determined by nutritional elements and specialized metabolites. Appropriate organic fertilization enhances beneficial microbial recruitment and optimizes rhizosphere microecology by supplying organic carbon and trace elements, thereby improving nutrient transformation and utilization. Tuna meal (TM), a major byproduct of the Japanese seafood processing industry, is rich in proteins and amino acids. After composting or other appropriate treatments, TM can be effectively utilized as a high-quality organic fertilizer in agricultural production. In this study, we examined changes in soil nutrients, rhizosphere bacterial communities, and tea shoot quality under different TM application ratios. Through integrated analyses, we elucidated the soil–microbe–plant interactions underlying the improvement of tea quality induced by TM application.

*Materials and Methods*— Tea seedlings (‘*Yabukita*’) were transplanted into Wagner pots (capacity: 1/5000 a; two plants per pot) and cultivated in a greenhouse at Shizuoka University (Shizuoka, Japan) in March 2025. The soil was reddish loess, and the TM fertilizer was supplied by Izugawa Feed Company (Shizuoka, Japan). The experiment included no-fertilizer and NPK controls, along with 25%, 50%, 75%, and 100% TM treatments, while maintaining equal total nitrogen input across treatments. Samples collected included rhizosphere soil, bulk soil, and new shoots. Soil physicochemical properties and bacterial communities were analyzed, and nutrient compositions in the aboveground tissues (including free amino acids (FAA), catechins, caffeine, and mineral elements) were quantified.

*Results*— (a) Soil nutrient analyses showed that different TM ratios significantly affected rhizosphere soil physicochemical properties. Soil pH remained within the acidic range suitable for tea growth (4.2–4.8) across all treatments. Electrical conductivity (EC) was highest under the 25% TM treatment. Potassium and inorganic nitrogen ($NO_3^-$-N and $NH_4^+$-N) reached their highest levels under the 25% and 50% TM treatments.
(b) Microbial community analysis identified *Proteobacteria*, *Actinobacteria*, *Chloroflexi*, and *Bacteroidota* as dominant bacterial phyla. Redundancy analysis demonstrated that fertilization markedly altered soil properties and bacterial community composition. Key environmental factors associated with bacterial variation included sodium, calcium, magnesium, and nitrate, while potassium and total nitrogen also contributed to community structuring. (c) Tea shoot quality analysis revealed that total FAA and caffeine were highest under the 25% and 50% TM treatments, whereas catechin levels increased progressively with higher TM proportions. Mantel tests further identified significant correlations between soil nutrients and tea shoot quality, between bacterial community structure and FAA, and between bacterial diversity and both caffeine and certain mineral elements.

Overall, moderate TM application enhances soil nutrient status and shapes rhizosphere bacterial communities, thereby promoting the accumulation of quality-related metabolites in tea shoots. These findings provide new insight into the mechanisms through which TM improves tea quality via soil–microbe–plant interactions and support its sustainable use as an organic fertilizer in tea cultivation.

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# Fractions of Phosphorus in Broiler Litter and its Fluxes in the Vadose Zone of a Transitioning Organic Farming System

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**ABSTRACT**

Alabama ranks second in broiler production in the United States, with an estimated annual production of over one billion birds and 1.5 to 2 million tons of broiler litter (BL). This BL (a waste) has been used in organic farming systems to supply phosphorus (P) for plant growth. Continuous applications of BL to soil have contributed to surface and groundwater contamination. Research work conducted in our laboratory has demonstrated that application of BL to soil increases organic and inorganic P contents of soil solutions. Transformations of the added organic P to soil affect P transport in the vadose zone. The objectives of the present studies were to investigate P transformations in BL-amended soils and to assess P fluxes in the vadose zone of a transitioning organic farming system. Suction lysimeters were installed on experimental plots located on a Marvyn sandy loam soil (fine-loamy, kaolinitic, thermic Typic Kanhapludults) at George Washington Agricultural Experiment Station at Tuskegee University with three lysimeters on each experimental unit at 30, 60, and 90 cm depths to allow for periodic water sampling. The pH of the water collected at each sampling occasion was measured and the volume recorded in the field, placed in an icebox, transported to the laboratory, and kept in a freezer until analysis. A portion of the water sample was filtered through a membrane filter (0.45 µm) and an aliquot analyzed for dissolved reactive P by direct colorimetry. Acid-hydrolyzable P following $H_2SO_4$ hydrolysis of the sample was determined in aliquots of filtered and unfiltered samples and total P was determined after ammonium persulfate digestion. Phosphorus in the water sample or in the acid digest was determined by the heteropoly blue colorimetric method as described by Murphy and Riley. Results showed that, before application of the fertilizers, the dissolved reactive P was the most dominant fraction of P in the water samples and varied between 0.05 and 0.28 mg $L^{-1}$ while the dissolved acid-hydrolyzable ranged between 0 and 0.10 mg $L^{-1}$, and the total organic P between 0.02 and 1.65 g $L^{-1}$. Application of fertilizers changed P dynamics in soil water solution, but inorganic P remained an important fraction of P found beyond the rooting zone of sweet potato. Understanding P dynamics in the vadose zone is a prerequisite to designing strategies to improve P nutrition and to prevent surface and groundwater pollution.

# Agronomic and Environmental Effects of Straw Incorporation in the Rice–Wheat Rotation Region of the Yangtze River Delta: Research and Application Demonstration

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## ABSTRACT

The Yangtze River Delta is a major rice–wheat rotation region in China. Straw incorporation is a critical pathway for the rapid recycling of crop residues, sustained improvement of soil fertility, and regional yield enhancement. Previous studies indicate that long-term straw incorporation increases soil organic matter (SOM) by 14–68%, available phosphorus and potassium by 2–3 times, and inherent soil productivity by 20–34%. However, systematic research is lacking regarding straw decomposition characteristics, SOM accumulation drivers, and environmental risk mitigation across different seasons and regions. The insufficient integration of these key technologies has constrained the large-scale adoption of straw incorporation strategies that balance rapid fertility improvement with environmental protection.

To address this, we established a province-wide monitoring network and clarified that soil, climate, and water resources are the main drivers of the agronomic and environmental responses to straw incorporation. We quantified the spatial distribution of straw under different incorporation modes, developed biological products to accelerate straw decomposition, elucidated the mechanisms of bioaugmentation-enhanced humification, and developed an integrated model for constructing a fertile plow layer via straw incorporation at optimal depths.

The results are as follows: Straw incorporation—particularly deep plowing—showed clear yield-increasing potential. In the wheat season, deep plowing significantly increased grain yield by 5–14%. Compared to rotary tillage and straw removal, deep plowing increased the tillage layer depth by 6–8 cm and SOM storage by approximately 26.5 t $ha^{-1}$, demonstrating a substantial advantage in building soil organic carbon stocks. Deep straw incorporation markedly promoted wheat root development, enhanced tolerance to drought and cold, and led to an additional average yield increase of over 8%. Furthermore, it significantly reduced the risk of non-point source pollution from surface runoff, decreased greenhouse gas emissions by 12.6%, and markedly lowered the incidence of pests, diseases, and weeds compared to rotary tillage.

Overall, deep straw incorporation in both seasons is the optimal practice. However, considering the tight turnaround time between wheat harvest and rice transplanting, potential delays caused by deep plowing, and increased equipment costs, we propose region-specific incorporation strategies. These comprise three modes: eco-economic balance, priority on carbon sequestration and soil improvement, and priority on environmental protection. Large-scale demonstration zones have been established for each mode.

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# The Influence of Organomineral Fertilizers and Biopreparations on Yield, Fruit Quality, and Soil Microbiological Properties under Golden Delicious Apple Orchards in Irrigated Light Chestnut Soils of Southeastern Kazakhstan

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**ABSTRACT**

This study investigates the effects of mineral and organomineral fertilization systems on the yield, fruit quality, and soil microbiological properties of Malus domestica cv. Golden Delicious grown in irrigated light chestnut soils of southeastern Kazakhstan (Omasheva et al., 2018). Field trials (2021–2025) were conducted on 3–4-year-old trees grafted on MM106 and M9 rootstocks. The experimental design included a control (no fertilizers), a mineral background ($N_{90}P_{90}K_{90}$) (Yefremova et al., 2023), and combinations of NPK with biopreparations (Agroflorin, Al Karal, BioSok Energy Plus) and vermicompost (Nasiyev et al., 2022; Maulenova et al., 2025).

Organomineral treatments increased yields by 39–64% relative to the control. The highest productivity (up to 295 c/ha) and longest storage life (up to 6 months) were achieved with NPK + vermicompost and NPK + BioSok Energy Plus. Fruit quality improved substantially: sugar content increased by 0.5–1.9%, and dry matter by 0.8–1.5%, compared with the control.

Rhizosphere microbiological analyses showed notable increases in ammonifying and nitrogen-fixing bacteria (Azotobacter), Pseudomonas spp., amylolytic forms, and microscopic fungi under organomineral treatments. These shifts indicate enhanced soil biological activity, improved nutrient cycling, and greater biological fertility.

The results demonstrate that organomineral fertilizer systems combined with biopreparations effectively enhance productivity and fruit quality in Golden Delicious orchards while strengthening soil microbiological functioning in irrigated light chestnut soils. Such systems represent a promising strategy for biologized and sustainable orchard management in arid and semi-arid regions of Kazakhstan.

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# Effects of Long-term Organic Fertilization in Tea Gardens on Soil Microbial Communities and Tea Quality

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## ABSTRACT

Various organic fertilizers have been widely applied in tea gardens in recent years, which could mitigate soil acidification and other negative effects caused by chemical fertilizer overuse. However, this remains an empirical agricultural practice, and there are still many unknowns about the actual effects including soil microbial ecosystems. In this study, we investigated the dynamics of soil microbial community and tea quality in tea gardens under long-term rapeseed cake and cow manure fertilization.

Three treatments were applied: (1) conventional fertilization (CK; 40 g $N \cdot m^{-2} \cdot yr^{-1}$), (2) organic fertilization with cow manure and rapeseed cake at a standard nitrogen rate (OF1; 40 g $N \cdot m^{-2} \cdot yr^{-1}$), and (3) organic fertilization with a higher nitrogen input (OF2; 56 g $N \cdot m^{-2} \cdot yr^{-1}$). Soil and leaf samples were collected over five consecutive months (December to April next year). This phase of the study builds on eight years of continuous field trials with fixed-position fertilization at our research site.

The results showed that organic fertilization significantly increased soil pH, total carbon, total nitrogen, exchangeable $Ca^{2+}$ and $Mg^{2+}$, demonstrating its ability in mitigating soil acidification and improving soil fertility. Organic fertilization also significantly altered soil microbial communities. Soil bacterial diversity was significantly higher than under conventional fertilization, while fungal diversity was lower. Meanwhile, for soil bacteria, soil pH and some exchange cations (K+, Mg2+, Ca2+) were positively related to the bacterial diversity and the abundance of soil phyla Bacteroidota, Patescibacteria, and Gemmatimonadota. For soil fungi, soil pH, NH4+-N, AP, Exch-Ca2+, and Exch-K+ were negatively related to the fungal diversity and phylum Ascomycota. Besides, a total of 8 phyla and 38 families were identified as key bacterial communities, and 8 families were identified as key fungal communities. About co-occurrence networks, the soil bacterial networks exhibited greater complexity, and the associations among soil bacteria were more interconnected under organic fertilization than in the fungal networks. In addition, the content of total FAAs in OF1 and OF2 was significantly higher than that in CK, and the content of total catechins in OF1 was significantly higher than that in OF2 and CK. In mature leaves, the mineral contents were influenced by both fertilizer management and sampling month. These findings suggest that organic fertilization can effectively mitigate soil acidification and improve tea quality by regulating soil microbial communities.

# The stability of softwood biochars and their impact on nitrogen retention in contrasting boreal soils over 14 years

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## ABSTRACT

Biochars as soil amendments have been reported to fix carbon and, in some cases, also improve soil ammonium ($NH^{4+}$) and nitrate ($NO^{3-}$) retention. However, biochar added to fields undergoes physicochemical changes and spatial migration under long-term environmental influences. Knowledge gaps remain regarding how biochar's nitrogen retention capacity changes over time and its migration patterns in the soil profile. We targeted these gaps by studying two long-term biochar field experiments in Finland where biochar was applied to soils (Stagnosol and Umbrisol) in 2010 and 2011, respectively. Firstly, we studied whether biochar was moving downwards in the soil profiles, from the 0-10 cm depth where it was originally applied to, and whether this movement was related to the soil type. Secondly, we tested whether the migrated biochar contents could explain N (especially $NO^{3-}$) contents across the soil profiles and thus provide $NO^{3-}$ retention capacity even in deeper soil layers long time after soil biochar soil application. We analyzed soil samples collected from 0–50 cm depth and divided these into 10 cm deep layers for analysis.

Results showed that in the Stagnosol field, the mean $NO^{3-}$ retention content in biochar-treated samples (9.16 mg $kg^{-1}$) was higher than that in control samples (7.14 mg $kg^{-1}$) at 10–20 cm depth, suggesting a trend toward a persistent effect of biochar on $NO^{3-}$ retention 14 years after application. Further characterization of biochar content and properties using benzene polycarboxylic acid (BPCA) molecular markers revealed that biochar remained present in soil after 14 years. In both fields, black carbon exhibited a downward leaching trend after 14 years. However, the downward migration extent of biochar varied between the two soil types. In the Stagnosol soil, the biochar content in the treated soil had migrated down to 30 cm depth, and the concentration at this depth remained significantly higher than the control. In contrast, in the Umbrisol soil, the difference in BC content between the treated and control groups became non-significant below the 20 cm depth. In the Stagnosol soil, clay content was significantly negatively correlated with biochar content ($p$=0.018), while no such correlation was found in Umbrisol soil. This suggests a contrast in retention mechanisms in both soils. In the Stagnosol soil, the clay fraction failed to provide effective stabilization and protection for BC in the main retention zone. Conversely, in the Umbrisol soil, BC retention is more likely governed by binding into stable aggregates with other soil components, which is independent of clay content. The study demonstrates that biochar can be preserved long-term in soil while maintaining $NO^{3-}$ retention capacity, reducing nitrogen loss, which has important implications for sustainable nitrogen fertilizer management.

# Effect of Biochar from Spent Media Growth on Kimchi Cabbage Cultivation in Upland Area

**Ji-Min Song[1], Chang-Gon Lee[1], Ikhyeong Lee[2], Han-Na Cho[2], Jae-Hong Shim[3], Sang-Gyu Lee[4], Yu-Deok Han[4] and Se-Won Kang[1,2*]**

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## ABSTRACT

The expansion of greenhouse horticulture and the advancement of controlled environment agriculture, including smart farming systems, have increased the generation of by-products and spent growing media in South Korea. This study evaluated the feasibility of converting these discarded media into biochar for use as an organic fertilizer. Spent growing media collected from a smart farm were dried and pyrolyzed at 400°C for 2 hours to produce spent growing media biochar (SGMB). The SGMB exhibited the following chemical characteristics: pH 10.2, total nitrogen (T-N) 1.24%, and total phosphorus (T-P) 0.33%. A cultivation experiment using kimchi cabbage (*Brassica rapa var*. glabra) was conducted under a randomized complete block design with four treatments and three replications. The treatments included a control (CN), inorganic fertilizer (IF; N–P–K = 300–78–198 kg ha$^{-1}$), and two biochar treatments, SGMB3 (3 t ha$^{-1}$) and SGMB5 (5 t ha$^{-1}$). The highest plant height was observed in SGMB3 (21.4 cm plant$^{-1}$) and SGMB5 (21.3 cm plant$^{-1}$), while the greatest leaf width, head diameter, and fresh weight were recorded in IF (12.5 cm plant$^{-1}$, 38.0 cm plant$^{-1}$, and 1453 g plant$^{-1}$, respectively). Although overall kimchi cabbage growth in SGMB treatments was slightly lower than that in IF, nitrogen use efficiency and soil chemical properties improved, and nitrous oxide emissions decreased. These results indicate that SGMB can enhance soil fertility and contribute to sustainable crop production as an organic fertilizer. Further studies should assess the long-term effects and optimal application rates of SGMB on crop performance and environmental outcomes.

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# Assessing the Agricultural Utilization Potential of Chicken Manure Biochar: Effects on Kimchi Cabbage Growth, Nitrogen Use Efficiency, and $N_2O$ Emissions in Upland Soil

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**ABSTRACT**

This study investigated the effects of chicken manure biochar (CMBC) application on the growth of kimchi cabbage (*Brassica rapa ssp*. pekinensis), nitrogen use efficiency (AE_N, agronomic efficiency of nitrogen; ARF_N, apparent recovery fraction of nitrogen), and nitrous oxide ($N_2O$) emissions in upland soil. Chicken manure and woody biomass were mixed at a ratio of 80:20 (w/w) and pyrolyzed at 400°C for 2 hours to produce CMBC. The experimental treatments consisted of a control (CN), an inorganic fertilizer treatment (IF; N 320 kg $ha^{-1}$, P 78 kg $ha^{-1}$, K 198 kg $ha^{-1}$), and three biochar treatments with CMBC applied at 3, 5, and 7 t $ha^{-1}$ (CMBC3, CMBC5, and CMBC7, respectively). Increasing CMBC application generally improved soil pH, electrical conductivity (EC), organic matter (OM), available phosphorus (Avail. $P_2O_5$), total nitrogen (TN), and cation exchange capacity (CEC). Kimchi cabbage growth also responded positively to CMBC, with fresh weight progressively increasing from 904 to 1,244 g $plant^{-1}$ for CMBC3 to CMBC7. The highest head height (23.2 cm $plant^{-1}$) was observed in CMBC7, and the overall growth performance followed the order IF > CMBC7 > CMBC5 > CMBC3 > CN. Nitrogen uptake increased with higher nitrogen inputs, with the highest uptake in IF (8.82 g $m^{-2}$), followed by CMBC7, CMBC5, CMBC3, and CN. Among the biochar treatments, CMBC7 achieved the greatest nitrogen use efficiency, with AE_N of 8.88 kg N $ha^{-1}$ and ARF_N of 26%. Both CMBC3 and CMBC5 showed higher nitrogen use efficiency than IF, indicating that CMBC enhanced nitrogen use by the crop. $N_2O$ emissions were highest in IF, decreased by 72.1%, 63.6%, and 59.2% in CMBC3, CMBC5, and CMBC7, respectively, with lower nitrogen application rates associated with reduced $N_2O$ release. Overall, CMBC application improved soil fertility, enhanced nitrogen use efficiency, and mitigated $N_2O$ emissions during kimchi cabbage cultivation. The optimal response was observed at 7 t $ha^{-1}$, suggesting that CMBC represents a promising organic amendment for sustainable crop production. Further research is needed to assess higher application levels and the long-term environmental implications of CMBC use in upland agroecosystems.

**Acknowledgments**

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# Development of sisal seedlings with solid organic substrates, based on sisal residues, in Brazil

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**ABSTRACT**

The circular economy is presented as a production and consumption model that involves sharing, renting, reuse, repair, and renewal. In the sisal sector, approximately 4% is used for the commercialization of the fiber (currently the main product sold), while the remaining 96% are byproducts characterized as defibration residues with 15% mucilage (cuticle + palisade and parenchymatous tissue), 1% sponge (short fibers), and 81% juice. These data demonstrate a potential utilization of 96% of the byproducts derived from sisal fiber production (Ferraz-Almeida et al. 2025). This study developed tests with the organic substrate "AgaveFert," based on sisal waste, for the production of sisal seedlings at the State University of Bahia. The system was established in a randomized block design, using 5 replications with 6 treatments: 2, 4, 6, 8 and 10 liters of substrate, and the control (without residue). Residues derived from sisal were collected in the Conceição do Coité region, on 10 different properties with varying soil management practices, to understand the quality of the residues for mixture formation. Results showed that plant mass of the aerial and root parts was greater with the application of sisal solid residues, comparing all doses with the control. The control presented a total plant mass (aerial and root) of 29.7 g/plant, as well as an average root and aerial system mass of 25.4 g/plant and 4.3 g/plant, respectively. The highest average total plant mass (aerial and root) was observed with the application of 12 liters of solid sisal waste, with an average of 247 g/plant, as well as with the application of 4 and 8 liters of solid sisal waste, with averages of 209.0 and 206.9 g/plant, respectively. The application of sisal solid waste promoted the aerial and root development of sisal plants, compared to soil without the application of sisal waste. Among the doses, it was not possible to identify the optimal dose, with a high variation between the doses of sisal solid waste, without a clear linear or quadratic behavior and an $R^2$ value less than 70%. This result indicates that there was no clear increase in plant production (linear or quadratic) with the application of sisal solid waste. Based on the results, it is concluded that the application of sisal solid waste is indicated, increasing the production of leaves and roots of sisal seedlings. Future studies are recommended with a greater variation of high and low doses to better identify the effect of solid waste on the development of sisal seedlings.

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# Long-Term Effects of Organic Manure on Rice Productivity and Soil Nutrient in Paddy Systems

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## ABSTRACT

**Background:** Long-term evaluation of soil nutrient dynamics under organic management is essential for understanding how sustained amendments influence crop performance, soil fertility, and agroecosystem resilience. In paddy soils, where anaerobic conditions, organic inputs, and nitrogen transformations interact in complex ways, monitoring multi-year changes provides critical insights into nutrient availability and the sustainability of rice production systems. For understanding long-term organic manure application on rice growth, this study investigates eight years of rice biomass production, soil organic carbon (SOC), total nitrogen (TN), and the carbon-to-nitrogen (C/N) ratio changes, a pot experiment with precise management was conducted at Tsuruoka campus, Faculty of Agriculture, Yamagata University, Japan, spanning from 2018 to 2025.

**Material and Method:** The experimental soil was collected from a long-term organic manure field in the Takasaka University Farm, Yamagata University, Japan. The field was applied heavy organic manure at 40 t $ha^{-1}$ more than 20 years. Four treatments were set up in this pot experiment. 1. Continued application organic manure at 40 t $ha^{-1}$ (40T); 2. Decreased the organic manure to the half at 20 t $ha^{-1}$ (20T); 3. Stop organic manure application (0T) and 4. No rice growth and no organic manure application (NP). Each treatment had 4 replications. The rice (Haenuki) was transplanting in the treatment pots excepted NP on end of May and harvested on the end of September, every year. Small size of soil samples also taken from the pots every year after harvest.

**Result:** As the results show, ear and aboveground biomass were highest in 2018, followed by a sharp decline in 2019, after which they remained low and relatively stable from 2020. Throughout most years, the 0T treatment produced higher rice biomass than the 20T and 40T manure treatments. This pattern is attributed to early-stage nitrogen immobilization, where microbes decomposing manure temporarily reduced plant-available nitrogen. Aboveground biomass showed a sharp decline after the high initial values in 2018, with all treatments dropping by 2019 and remaining low in 2020-2023. By 2024–2025, manure treatments, especially 40T, continued to show gradual improvement, where 0T consistently stayed lower, showing a long-term transition from early nitrogen immobilization to more favourable nitrogen mineralization in later years. Similarly, the harvest index was highest in 2018 across all treatments, followed by a decrease in 2019–2020. From 2024 to 2025, the harvest index remained relatively stable, with modest differences among treatments, showing that the balance between grain yield and aboveground biomass became more consistent as the system stabilized over time. Soil depth also decreased across treatments from 2018 to 2020, with 40T, 20T, 0T, and NP each showing a sharp drop after the initial year. In 2022, 40T and 0T showed slight increases in soil depth, while 20T and NP remained lower, reflecting differences in soil settling and the stabilizing effects of organic inputs. From 2023 to 2025, soil depth gradually stabilized, with 40T maintaining the greatest depth, 20T showing moderate recovery, 0T continuing a mild decline, and NP remaining the lowest, indicating that higher manure rates helped preserve soil volume over time.

**Conclusion:** Overall, the 0T treatment produced the highest aboveground biomass and often the highest harvest index, manure levels of 20T and 40T frequently resulted in lower early-year values, likely due to nitrogen immobilization during initial years of organic input. Despite these fluctuations, long-term trends show gradual improvement in both biomass and harvest index toward the later years of the experiment. The SOC and TN results will be shown in the congress presentation.

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# Fermentation Characteristics of Sawdust-Bokashi and its Effect on Soil Fertility and Pepper (Capsicum spp.) Performance.

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**ABSTRACT**

Poor soil fertility is a major constraint to food production in Nigeria. The use of agro-waste as organic amendment is sustainable, and a panacea to improving soil fertility and crop yield. This work was carried out in 2024 and 2025 to evaluate the characteristics of fermented saw dust-bokashi (SDB) and its effects on soil properties and the performance of pepper. The fermentation process lasted for 12 days, during which, temperature, pH, moisture, and bulk density were monitored. Fermented SDB was applied on day 13. Six pot treatments were tested: control, 0.8 t $ha^{-1}$ NPK, and bokashi at 15, 18, 21, and 24 t $ha^{-1}$. The treatments were arranged in a completely randomized design (CRD), with three replications. Chemical properties of fermented SDB, as well as pre and post-planting soil attributes, were analyzed. Growth and yield parameters of pepper were measured. The data generated from the effects of the various treatments on soil and plant performance were analyzed using Analyses of Variance (ANOVA) while those from fermented and unfermented bokashi were analyzed using T-test. Significant means were separated using LSD at 5% probability. Results revealed changes in temperature (30.38°C to 51.79°C), pH (7.00 - 9.12), and moisture (27.00% to 57.00%) during fermentation. 12 weeks after treatment application, results showed that the application of bokashi significantly improved soil pH (5.45 to 6.65), organic carbon (0.96% to 2.94%), total nitrogen (0.19% to 0.26%), and available phosphorus (20.58 $mgkg^{-1}$ (control) to 38.66 mg $kg^{-1}$ in 24 t $ha^{-1}$ bokashi. Exchangeable calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) also increased significantly across treatments, with the highest values observed at the 24 t $ha^{-1}$ bokashi rate. Between 2 and 4 weeks after transplanting (WAT), the unfertilized soils had significant higher plant growth parameters. From 8 WAT onward, bokashi-treated soils generally produced the highest growth parameters with 15 t $ha^{-1}$ and 21 $tha^{-1}$ bokashi rates giving the best performance. The highest number of pepper fruits was also recorded in 15 and 21 t $ha^{-1}$ bokashi rates. The study showed that amending degraded soil with bokashi improved the soil pH, fertility, growth and yield of pepper and these improvements manifested more when 15 $tha^{-1}$, 21 t $ha^{-1}$ and 24 t $ha^{-1}$ were applied. In addition, the study revealed the potential of SDB as a superior alternative to conventional fertilizer.

Keywords: bokashi, degraded soil, fermentation, inorganic fertilizer, soil fertility, sawdust

# Use of organic viticulture wastes as soil amendments to improve the function of clay soil in the Waipara region, New Zealand

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**ABSTRACT**

Viticultural waste streams, such as grape marc and vineyard prunings, pose ongoing environmental and economic challenges for New Zealand's wine industry. Transforming these waste materials into compost or biochar offers a promising circular solution that can simultaneously reduce waste volumes and provide valuable soil amendments. Our research sought to test the potential of compost and biochar produced from organic vineyard waste to improve clay soil properties and support the establishment of native plants in New Zealand.

We established a field trial at a vineyard in the Waipara wine-producing region in April 2025, with application rates of 2 % and 4.8 % for biochar and compost, respectively. Topsoil samples were collected three weeks after application, using 7.5 × 7.5 cm cores for physicochemical characterisation. We found that both biochar and compost substantially decreased soil bulk density from 1.19 to roughly 0.96 g $cm^{-3}$ and increased soil pH from 5.82 to 6.02 and 6.58, respectively. The biochar amendments also enhanced soil water holding capacity at −10 kPa, however, gas diffusivity has so far remained unchanged. We also report longer-term outcomes on soil carbon sequestration and fertility, as well as effects on plant biomass and nutrient uptake. Our findings will help inform the broader agronomic and environmental value of integrating these amendments into vineyard waste and soil management practices.

**Keywords**

Biochar, compost, vineyard wastes, clay soil

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# Nitrogen waste in cropping and livestock systems of Darusa village, Bangladesh

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**ABSTRACT**

To assess methods to reduce nitrogen waste, a survey of farming practices was conducted in Darusa village, Bangladesh. A total of 100 households were surveyed to determine demographic and agricultural information. Four clusters of farms were identified and nine households randomly selected from each. Detailed surveys on cropping and livestock, and nitrogen contents of imported and exported products were used to estimate nitrogen waste on these 36 farms. Clusters of farms were (cluster-1) high irrigation / high livestock, (cluster-2) low irrigation / low livestock, (cluster-3) low irrigation / high livestock and (cluster-4) medium irrigation / low livestock. Nitrogen waste across crops and livestock in Darusa village reveals substantial inefficiencies in nutrient management. *Nitrogen waste from wheat and lentils* was lower than other crops, while from early kharif (summer-monsoon) rice and rabi (winter) potatoes and onions, waste was significantly higher, indicating clear opportunities for reducing fertilizer inputs in these crops. Nitrogen waste was lowest on farms with low livestock, particularly those with only poultry and ducks. It was significantly higher on farms with cattle and buffaloes reflecting the likely use of cattle and buffalo manure as fuel. The findings suggest that reduced nitrogen waste could be achieved by (1) reducing nitrogen inputs to kharif-rice and rabi-potatoes, (2) reducing number of livestock or improving use of manure and urine to improve soil fertility and (3) increasing recycling of other organic residues to crops. The average savings in synthetic fertilizers across the village highlight a substantial reduction in synthetic fertilizer requirements when manure is effectively utilized. This indicates that using manure not only reduces dependence on synthetic fertilizers but also lowers production costs.

**Keywords:** Nitrogen waste index, cropping N source, livestock N source, nitrogen management, synthetic fertilizer savings.

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# Biogeochemical and Isotopic Responses on Soil Health Following Dairy Manure Compost Application in an Almond Orchard

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## ABSTRACT

Exporting manure from large dairies and utilization as an organic amendment is a viable pathway for reducing potential on-site nutrient overloading, mitigating greenhouse gas (GHG) emissions, and efficient provisioning of nutrients for crop uptake. Such synergies can arise between industries to meet sustainability and economic goals which can support a circular nutrient economy. However, utilization of dairy manure compost (DMC) in conventional commercial almond orchards and its impact on soil health and biogeochemical cycling is not yet fully understood. Unravelling key factors that underlie mechanisms of emissions mitigations and effects on yield is critical to effective management and broader adoption. To investigate how DMC derived carbon, in tandem with fertigation, affect the microbial community's processing of nitrogen (N), its resulting control on attributable emissions of nitrous oxide ($N_2O$), and soil health response an orchard with microsprinkler fertigation-irrigation was divided into four blocks. Each has established a control of no DMC/fertigation (0C, 0N), DMC only (+C, 0N), fertigation only (0C, +N), and DMC + fertigation (+C, +N). DMC soils had 8 metric tons dry weight per hectare (ha) applied. Soils that received synthetic N had 100 kg N/ha applied over three applications. Yearly DMC application is targeted during Fall after harvest from 2021 through 2024. To assess interactive effects of DMC/fertigation on soil health/physicochemical properties event related soil samples (topsoil 0 - 15 cm, 1-m cores), GHG flux via LI-COR TGA system, hydraulic conductivity, and yield data were collected. $N_2O$ fluxes observed were largely event driven, though a significant reduction was observed for +C,+N relative to 0C,+N during and after fertigation. Soil inorganic N between treatments show no significant difference, though dissolved organic carbon and nitrogen were significantly higher in DMC soils. To explore mechanistic processes a $^{15}N$ isotope dilution via mineralization-immobilization turnover was conducted in-field along with a $^{15}N$ tracer experiment. Tracer gas samples were analyzed for $N_2O/N_2$. In addition, the potential of natural abundance $N_2O$ isotopomer ratios for predicting dominant microbial nitrogen processes was evaluated. Significant differences in site pReferences between treatments before and after fertigation were found. Almond yield in +C,+N treatments were consistently higher than 0C,+N. In addition, GHG reductions were achieved without lowering N inputs while co-benefits such as improved soil structure and tree vigor were measured. Work in progress involves identifying N genes via metagenomics and community identification via 16s sequencing.

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# Effect of Pusa Decomposer-mediated rice residue management on soil phosphorus dynamics in a rice–wheat system of the Indo-Gangetic Plains

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**ABSTRACT**

Despite several alternatives to rice residue management have been proposed, there remains a notable gap in understanding how these practices, particularly the use of microbial decomposers and residue management affect soil phosphorus (P) fractions and related biological properties in a rice-wheat cropping system. Widespread rice-straw burning persists especially in Haryana, western Uttar Pradesh, and Punjab of India because of short sowing windows and limited residue-handling options, leading to nutrient loss, greenhouse gas (GHG) emissions, and soil carbon decline which is essential for soil functioning. Promoting in situ residue incorporation offers a sustainable alternative, and the Pusa Decomposer has emerged as an effective, rapid, and scalable solution for improving straw decomposition and soil health. This fungal consortium comprises efficient lignocellulolytic strains capable of accelerating straw degradation within 20–25 days under field conditions, significantly improving organic matter turnover, nutrient availability and soil health. While the positive effects of Pusa Decomposer on straw decomposition, carbon dynamics and microbial activity have been increasingly recognized, its specific influence on soil P dynamics remains inadequately understood. To address this gap, a three-year field experiment (2021-2024) was laid out in a randomized block design comprising five treatments: full residue burning, full residue retention, full residue incorporation, full residue retention with Pusa Decomposer, and full residue incorporation with Pusa Decomposer, each replicated four times to evaluate the impacts of different rice residue management strategies with and without the application of the Pusa Decomposer on soil P fractions and biological indicators in bulk soils and soil aggregates. Soils sampled were collected at the end of the third year of the experiment from 0-15 and 15-30 cm soil layers and analysed for soil aggregation and P fractions in bulk soils and aggregates. The results showed that the full residue incorporation with Pusa Decomposer treatment significantly increased labile and water soluble P, sorbed P, easily mineralizable organic P and moderately labile P fractions, as well as total P, total inorganic P and enzymatic activities compared to the residue burning treatment in the surface soil layer, with consistently higher values observed in bulk soils than soil aggregates. Full residue incorporation treatment exhibited the highest levels of hydrochloric acid extractable P and residual P which were notably more concentrated in aggregates than in bulk soils. Complete residue incorporation led to the highest accumulation of hydrochloric acidextractable P in macroaggregates, whereas residual P was mostly concentrated in microaggregates. These findings highlight the potential of integrated residue and Pusa Decomposer management strategies, to enhance soil nutrient availability, while reducing reliance on external P inputs in intensive rice based systems. Integrating residue incorporation practices with microbial consortia such as Pusa Decomposer is an effective strategy to enhance soil P availability and stimulate soil biological activity in an intensive rice–wheat system, offering a pathway towards more sustainable nutrient management.

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# Metagenomics reveals microbial regulation of soil nitrogen retention and supply under nitrogen fertilizer reduction with long-term residue retention

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## ABSTRACT

Improving soil fertility can reduce the need for nitrogen (N) fertilizer application and mitigate agricultural N losses to the environment. Crop residue return is one of effective practices to improve soil function on N retention and supply, thereby providing a prerequisite for substantial reductions in N fertilizer application. However, the underlying mechanism of how microorganisms involved in different transformation processes respond to N fertilizer reduction under long term residue return remains largely unknown. Here, a three-year N fertilizer reduction experiment was conducted following nine years of continuous stover mulching in a Mollisol of Northeast China. Metagenomic sequencing was used to investigate the response of key functional genes of microbial N cycling to fertilization regimes. Compared with conventional N fertilization application rate (240 kg N $ha^{-1}$, CK), reducing fertilization rate to 190 kg N $ha^{-1}$ (N190) elevated the abundance of the genes involved in organic N mineralization (UreC and pepA), assimilatory nitrate reduction to ammonium (ANRA, nasA) and dissimilatory nitrate reduction to ammonium (DNRA, napA and nirB), thereby maintaining soil N availability by favoring $NH_4^+$ retention, stabilizing microbial N-cycling networks, and supporting plant N uptake. Further reduction of N application to 135 kg N $ha^{-1}$ (N135) resulted in a slight N deficit on account of N balance in the soil-crop system, while the maize yield remained unchanged throughout the three growing seasons. Under this condition, microbial communities shifted from copiotroph-dominated to oligotroph-dominated, accompanied by a weakened microbial N cycling network, likely reflecting a strategy to reduce their N demand Compared with CK, the higher abundance of genes involved in DNRA and lower abundance of genes involved in denitrification in N135 treatment likely sustained soil $NH_4^+$ concentration for plant uptake, while simultaneously reducing soil $NO_3^-$ concentrations and mitigating N losses. When N fertilizer input was completely ceased (0 kg N $ha^{-1}$), severe N deficiency constrained both microbial proliferation and crop yield. To compete with plant for N, microbes enhanced their ability for N retention by enriching genes involved in DNRA and ANRA at greater extent, and reduced N loss potential by suppressing nitrification and denitrification processes. Overall, our results demonstrated that under conditions of consecutive maize residue return for maintaining C availability, there is substantial potential for N fertilizer reduction in black soil of Northeast China. The study comprehensively improves our understanding of microbially mediated soil N transformation and provides a scientific basis for sustainable agricultural management.

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# Comparison of organic and inorganic amendments for conserving soil moisture and increasing crop yield in wheat under water limited conditions

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**ABSTRACT**

Water scarcity is the main challenge for crop production under rainfed cropping systems. The present study was undertaken to compare the effectiveness of different organic and inorganic amendments to increase soil water retention and crop yield under rainfed conditions. A field experiment was conducted using different amendments i.e. T1 (control), T2 compost @ 750 kg $ha^{-1}$, T3 biochar @ 1000 kg $ha^{-1}$, T4 gypsum @ 1000 kg $ha^{-1}$, and T5 hydrogel @ 15 kg $ha^{-1}$. Two wheat varieties, Wafaq-2023 (V1), and NARC-Super (V2) were grown till maturity following the recommended agronomic practices. The results indicated that among the amendments, hydrogel was the most effective treatment followed by gypsum, biochar and compost, respectively for increasing grain yield and nutrient uptake by wheat. Under the application of hydrogel, grain yield was increased by 29 and 24%, and straw yield was increased by 28 and 23% in V1 and V2, respectively compared to control. The application of gypsum caused 20 and 14% increase in grain yield, and 19 and 15% increase in straw yield in V1 and V2, respectively. Under the application of hydrogel, Chl-a, Chl-b, relative water contents and stomatal conductance were increased by 55, 56%, 52 and 54% in V1 and by 36, 43, 42 and 43% in V2, respectively as compared to the control treatment. The accumulation of macro and micronutrients was also higher under hydrogel followed by gypsum application. The higher grain yield and nutrient uptake was attributed to better soil properties and soil water retention potential of hydrogel and gypsum as compared to the other amendments. It was concluded that hydrogels and gypsum are promising options along with wheat variety Wafaq-2023 for getting higher crop yield with better nutritional quality under rainfed conditions.

**Keywords:** Water scarcity, Climate change, Soil amendments, Rainfed areas, Wheat

# Study on the Effects of Different Organic Materials on Soil Humus and Nutrients

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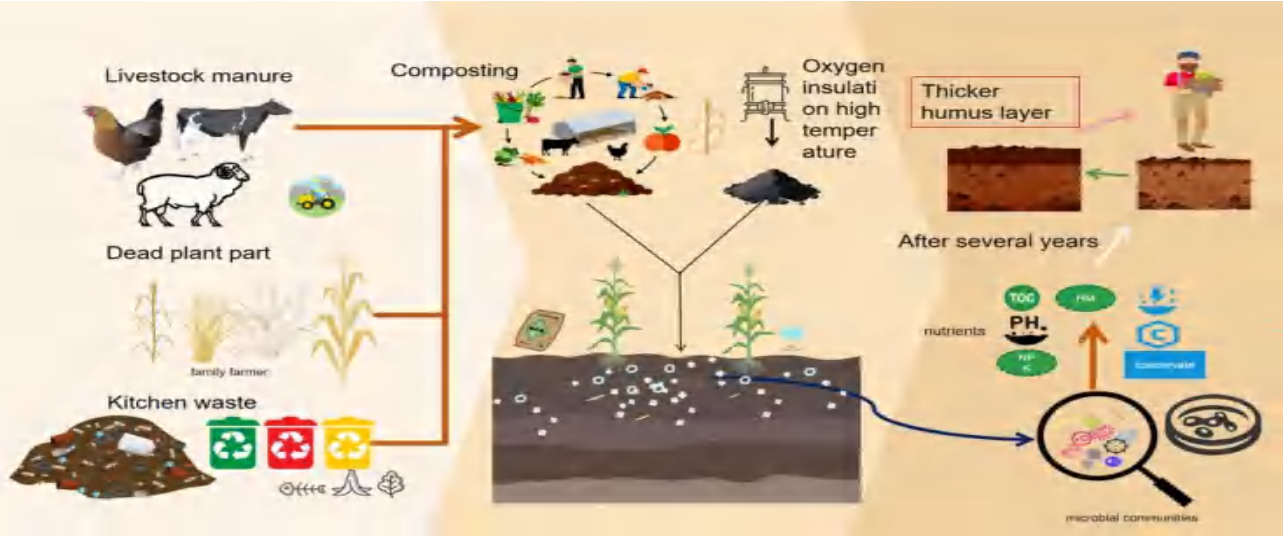
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## ABSTRACT

Based on field experiments, this study explored the effects of different organic materials on soil humus and nutrients, clarified the effects of different organic materials on soil fertility improvement and soil amelioration, so as to provide a scientific basis for optimizing fertilization schemes and improving soil quality.A field experiment was conducted at the Zheng Experimental Base in Nong'an County in 2023. Three types of materials were used in the experiment design, namely kitchen waste (CY), crop straw (JG) and cow manure (NF). Each material was processed into organic fertilizer and biochar, resulting in a total of seven treatment groups:CK (no organic materials added)、CYC (kitchen waste biochar)CYF (kitchen waste organic fertilizer)、JGC (crop straw biochar)、JGF (crop straw organic fertilizer)、NFC (cow manure biochar)、NFF (cow manure organic fertilizer).The effects varied among different organic materials. The NFF treatment increased soil pH. The improvement effect of organic materials on soil nutrients was more significant in the second year after application. Compared with CK, CYC and CYF treatments significantly increased the available nitrogen content by 17.72% and 27% respectively. All organic material treatments significantly increased the available potassium content by 5.02%–19.86%, with the highest content observed in the JGC treatment. Except for NFC, all other treatments significantly increased the available phosphorus content by 10.53%–52.96%. Meanwhile, the available copper content was significantly increased by 19.29%–54.12% in all treated groups, and the soil organic carbon content was also significantly elevated. Specifically, the JGC treatment significantly increased the contents of available zinc, iron and manganese by 73.04%, 19.40% and 10.29% respectively.

In terms of humus components, compared with CK, the NFC treatment significantly increased the fulvic acid (FA) content by 27.90% and also had a significant promoting effect on the water-soluble substance (WSS) content. The NFF treatment increased the humic acid carbon content by 34.30%. The JGF treatment significantly increased the humic acid/fulvic acid ratio and the PQ value of soil, while reducing the HAΔlogK, indicating that the humus tended to be "younger".

In conclusion, different organic materials exert distinct effects on soil properties, and the effects of biochar and organic fertilizer processed from the same raw material also differ. Among all treatments, JGC is conducive to the accumulation of trace elements and available potassium, while NFC and NFF treatments are favorable for the increase of humus carbon components and available phosphorus content.



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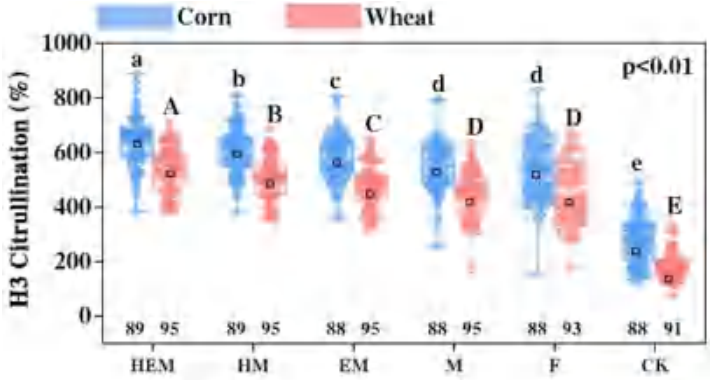
# Long-term field trials as a tool to evaluate the potential of compost to maintain grain yield and soil carbon persistence

**Zeyu Zhang[1], Zixun Chen[1], ZhangLiu Du[1], Yuquan Wei[1,2], Ting Xu[1,2], Anisur Rahman[1], Guochun Ding[1,2], Ji Li*[1,2]**

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**ABSTRACT**

Realistic estimation of the effects of organic amendment with compost on yield increase and soil carbon storage in agricultural soils requires long-term field experiments, as the stability of yield and soil organic carbon (SOC) is strongly influenced by spatiotemporal heterogeneity. Based on a long-term field experiment established in Quzhou County, Hebei Province, China in 1993, this study evaluated the dynamic characteristics of wheat and maize yields and soil organic carbon under the application of bio-compost and traditional compost. Over the more than 30-year experimental period, compared with the chemical fertilizer control treatment, the application of high-dose bio-compost showed a significant yield-increasing effect: maize and wheat yields increased by 19.38% and 23.62%, respectively; compared with traditional compost, maize and wheat yields increased by 5.56% and 4.97%, respectively. Compared to chemical fertilization, soil amended with bio-compost and traditional compost exhibited increases in SOC of 95% and 91%, respectively, in 2018. An increasing temporal trend in SOC content was observed under bio-compost application during the first nine years of the experiment. However, this pattern diminished after 2002, as insignificant correlations between SOC and time were found in bulk soil, microaggregates (particle size 53–250 μm), and mineral-associated organic matter (particle size < 53 μm). In contrast, SOC in coarse particle organic matter (particle size > 250 μm) continued to increase over time after 2002, indicating that SOC was persistently stored in macroaggregates (Chen et al., 2024). Between 2002 and 2020, compared with low-dose bio-compost, the high-dose bio-compost mode increased soil organic carbon content by 11.5%-32.6%, with an average annual growth rate of soil organic carbon of approximately 0.34%. This paper will discuss the potential of compost application in improving grain production capacity, mitigating the impacts of global warming, and maintaining long-term soil organic carbon storage.




**Key Words:** Bio-compost, Yield increase, Soil carbon storage, Soil aggregates, Long-term field trail

**References**

Chen, Z., Du, Z., Zhang, Z., Wang, G., and Li, J., Dynamic changes in soil organic carbon induced by long-term compost application under a wheat-maize double cropping system in North China. Science of the Total Environment 913 (2024) 169407.

**Acknowledgments**

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# Synergistic Effects of Long-term Biochar Application on Soil Fertility, Microbial Biomass, and Rice Yield in Paddy Fields

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**ABSTRACT**

Biochar holds great potential for improving soil fertility and enhancing crop yield, but its long-term effects on soil carbon and nitrogen components, microbial activity, and rice yield under continuous nitrogen fertilization remain unclear. A seven-year (2019-2025) field experiment was conducted in the high-fertility rice region of the Jianghan Plain, China, with four treatments: CK (no nitrogen control), CF (conventional nitrogen fertilization), CF+LB (conventional nitrogen plus low-rate biochar, 25 t/ha), and CF+HB (conventional nitrogen plus high-rate biochar, 50 t/ha). Rice yield components and growth indicators were monitored annually, and soil samples from 0-10 cm and 10-20 cm layers were collected in the 2025 harvest season to determine physicochemical properties, catalase activity, total organic carbon (TOC), total nitrogen (TN), and microbial biomass carbon and nitrogen (MBC, MBN).The results showed that, compared with the nitrogen-only treatment (CF), biochar applications (CF+LB and CF+HB) resulted in an average yield increase of 5.8% and 11.0% over seven years. However, the yield enhancement declined in the later years of the experiment. Yield increase was primarily attributed to significant increases in effective panicle number and plant height. Low-rate biochar primarily increased organic carbon in the 0-10 cm soil layer by 38.4%, while high-rate biochar significantly promoted carbon and nitrogen accumulation in the 10-20 cm layer, with TOC and TN increasing by 72.6% and 128.1%, respectively. Moreover, catalase activity was significantly enhanced. Biochar treatments also significantly increased MBC and MBN in both soil layers, with the CF+HB treatment showing the greatest effect. In the 0-10 cm layer, MBC and MBN increased by 21.4-30.1% and 63.7-115.9%, respectively.Structural equation modeling (SEM) analysis indicated that biochar promoted rice yield by increasing soil carbon and nitrogen levels, enhancing microbial biomass and enzyme activity, and improving rice growth indicators and yield components. In conclusion, long-term biochar application, especially at high rates, can synergistically improve soil carbon-nitrogen pools and microbial activity, leading to enhanced rice yield, providing a scientific basis for sustainable agriculture in high-fertility paddy regions.

**Keywords:**
Rice yield; Soil carbon-nitrogen pools; Microbial biomass; Enzyme activity; Structural equation modeling

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# Partial Substitution of Chemical Nitrogen Fertilizer with Organic Fertilizer Enhances Rice Yield by Improving Soil Microbial Activity and Optimizing Soil Nitrogen Supply

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**ABSTRACT**

The partial substitution of chemical nitrogen (N) fertilizer with organic fertilizer is a key strategy for reducing chemical fertilizer input and promoting green productivity in rice systems. However, the integrated mechanisms underlying its effects on rice yield enhancement and soil fertility improvement remain unclear. To address this, a seven-year (2019-2025) field experiment was conducted with six N application treatments: no N ( N0), chemical N-only at 60, 120, and 225 kg N $ha^{-1}$ (N60, N120, N225), and two combined treatments: 60 kg N $ha^{-1}$ chemical N+165 kg N $ha^{-1}$ organic N (N60+F165) and 120 kg N $ha^{-1}$ chemical N+105 kg N $ha^{-1}$ organic N (N120+F105). We systematically measured rice yield and its components (effective panicles, filled grain number per panicle, seed setting rate, 1000-grain weight), key growth parameters (tiller number, plant height, LAI, SPAD), soil profile mineral N content, soil physicochemical properties, microbial biomass carbon and nitrogen (MBC, MBN), and activities of four key soil enzymes (catalase, urease, sucrase, and neutral phosphatase). This study investigates the long-term effects and integrated mechanisms of partial organic substitution on rice yield, soil N retention, and fertility enhancement. The results showed that the N120+F105 treatment achieved the highest rice yield, which increased by 3.08%-17.60% compared to the N225 treatment. While maintaining a high leaf area index and tiller number, N120+F105 significantly increased the contents of soil organic matter, total N, available phosphorus, and available potassium in the plow layer. It also enhanced the retention of mineral N within the 0-20 cm soil layer, thereby reducing the risk of leaching into deeper soil. Furthermore, N120+F105 markedly improved soil microbial activity. In the 0-10 cm layer, MBC and MBN increased by an average of 30.3% and 112.0%, respectively, compared to N225. Synchronous increases in MBC and MBN were also observed in the 10-20 cm layer, and the microbial C/N ratio indicated that organic amendment alleviated N limitation in the deeper soil. Structural equation modeling further revealed that the organic substitution treatments primarily enhanced soil fertility and microbial biomass, which consequently improved soil N supply capacity, ultimately promoting rice tillering and effective panicle formation to increase yield. In conclusion, the appropriate partial substitution of chemical fertilizer with organic fertilizer (N120+F105) enhances rice yield and soil health synergistically by boosting soil microbial activity and optimizing soil nitrogen supply.

**Keywords**

Soil properties; Microbial biomass carbon and nitrogen; Structural equation modeling; Enzyme activity; Soil profile mineral nitrogen content

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# Decomposition characteristics of different organic materials and their effects on the carbon fractions of soil organic carbon in arable black soils

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**ABSTRACT**

Crop straw, livestock manure, and mushroom bran constitute the major agricultural organic wastes. Their incorporation into soils has been widely recognized as an effective strategy to enhance soil organic carbon (SOC) sequestration and improve soil fertility, thereby supporting sustainable agricultural development. Although numerous studies have examined the decomposition of different organic materials and their effects on soil quality at local or site-specific scales, regional-scale comparisons of decomposition characteristics and associated carbon chemical transformation processes across contrasting organic materials remain limited.

To address this knowledge gap, field decomposition experiments were conducted across five locations distributed along a south–north transect of the typical black soil belt in Northeast China. The dynamic decomposition characteristics of six organic materials—decomposed chicken manure, pig manure, mushroom bran, and soybean, maize, and rice straw—were investigated under equivalent carbon input conditions. Fourier transform infrared spectroscopy (FTIR), solid-state $^{13}C$ nuclear magnetic resonance ($^{13}C$ NMR), UV–visible absorption spectroscopy, and fluorescence spectroscopy were integrated to characterize the chemical transformation of organic materials during decomposition at the regional scale. In parallel, the coupled dynamics between organic material decomposition and changes in SOC quantity, fractions, and chemical structure were systematically analyzed.

This study elucidates the key factors regulating organic material decomposition and their roles in soil fertility enhancement, providing mechanistic insights into the transformation of organic inputs into soil organic matter. The findings offer a theoretical basis for improving the efficient utilization of agricultural organic waste resources and optimizing farmland management practices in the black soil region of Northeast China.

# The influence of organic materials on the chemical structure of humus in salt crust aggregates in the Yellow River Delta

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**ABSTRACT**

To investigate the potential of organic amendments for improving saline-alkali soils in the Yellow River Delta, a field experiment was conducted using saline fluvo-aquic soil in Dongying City. This study systematically compared the effects of biochar and cattle manure, applied individually and in combination, against the application of chemical fertilizer alone. The objective was to assess their efficacy in reducing soil salinity, enhancing soil organic carbon, and modifying the chemical structure of humus. Fourier transform infrared spectroscopy was employed as the principal analytical method to elucidate the mechanisms through which organic materials influence the chemical structure of humus within different particle-size fractions of soil aggregates. The key findings are summarized as follows:

(1) Significant Increase in Humus Components. The application of organic materials markedly promoted the accumulation of humus components across all aggregate size fractions. Specifically, the combined application of biochar and cattle manure (ABM treatment) demonstrated the most pronounced effect compared to the control (CK, no organic materials). In the 2–0.25 mm fraction, the organic carbon content of humic acid (HA), fulvic acid (FA), and humin (HU) increased significantly by 28.83%, 3.73%, and 41.69%, respectively, under ABM treatment relative to CK. Corresponding increases in the 0.25–0.053 mm fraction were 25.63%, 9.78%, and 29.86%. Notably, this enhancing effect persisted even in the <0.053 mm micro-aggregate fraction, with observed increases of 20.13% for HA, 7.92% for FA, and 29.82% for HU.

(2) In the 2–0.25 mm fraction, the application of biochar and cattle manure significantly increased the relative content of aliphatic, aromatic, and polysaccharide compounds in HA and HU, while also enhancing the aliphatic and aromatic characteristics of FA. This trend was consistent in the 0.25–0.053 mm fraction, where HA showed increased relative content of aliphatic, aromatic, and polysaccharide substances, and FA exhibited increased aliphatic and aromatic components. These findings provide a valuable theoretical foundation and practical References for utilizing organic amendments to improve saline-alkali soils, boost soil carbon sequestration, and foster sustainable agriculture in the Yellow River Delta.

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# Short-Term Soil Fertility and Crop Yield Responses to Municipal Organic Waste

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**ABSTRACT**

The application of organic waste materials represents an important approach for improving soil fertility while supporting circular economy principles. However, field-scale evidence on the short-term agronomic effects of different organic amendments remains limited, particularly for carbonate, alkaline soils. This study evaluated the first-year effects of sewage sludge, compost derived from sewage sludge, and sewage sludge combined with biochar on soil chemical properties and forage sorghum productivity under field conditions.

A field experiment was established in April 2025 at the Regional Landfill Subotica–Bikovo (Serbia) on a carbonate-rich clay loam soil. The trial included a non-amended control, sewage sludge, compost derived from sewage sludge, and sewage sludge combined with biochar, arranged in a two-factor design with four replicates. Organic amendments were applied at rates of 14 t $ha^{-1}$ for sewage sludge and compost and 12.2 t $ha^{-1}$ for biochar. Forage sorghum was cultivated as an industrial and energy crop, and soil samples were collected from 0–30 and 30–60 cm depths, while aboveground fresh biomass yield was determined at the first harvest.

Organic amendments induced clear treatment-specific changes in soil chemical properties, with responses mainly observed in the 0–30 cm layer during the first growing season. Compost application resulted in a balanced improvement of soil fertility, reflected by increased soil organic carbon and humus content, accompanied by higher availability of phosphorus and potassium and moderate mineral nitrogen levels, consistent with its biologically stabilized nature. In contrast, sewage sludge application substantially increased total and mineral nitrogen as well as available phosphorus, indicating a strong nutrient input but with greater variability compared to compost.

The combined application of sewage sludge and biochar resulted in lower mineral nitrogen and available phosphorus compared to sewage sludge alone, despite comparable levels of soil organic carbon. This response suggests short-term nutrient immobilization or sorption processes associated with biochar addition, likely affecting nitrogen and phosphorus availability in the initial phase after application. As a result, nutrient supply to plants was constrained during the first growing season.

Differences in soil chemical properties were directly reflected in forage sorghum performance. Compost-amended plots achieved the highest aboveground fresh biomass yield, consistent with improved nutrient availability and a balanced soil fertility status. Sewage sludge resulted in intermediate yields, reflecting its high nutrient input but less consistent nutrient availability under field conditions. In contrast, the sewage sludge and biochar treatment produced the lowest biomass yield, confirming that short-term nutrient immobilization can outweigh potential benefits of carbon stabilization during the first year after application.

**Key words:** Soil fertility; Organic amendments; Forage sorghum; Biochar

**Acknowledgments** This research was supported by the Science Fund of the Republic of Serbia, # 6769, Natural based efficient solution for remediation and revitalization of contaminated locations using energy crops - ReNBES

# Mechanisms of Biochar and Cattle Manure in Regulating the Microstructure of Humic Substances within Saline Fluvo-Aquic Soil Aggregates

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**ABSTRACT**

This study investigates the effects of individual and combined applications of biochar (AB) and matured cattle manure (M) on the chemical structure of humic substances within soil aggregates in saline fluvo-aquic soil of the Yellow River Delta. A field experiment was established in April 2019, and surface soil samples (0–20 cm depth) were collected in November from Maotuo Village, Dongying City (37°49′15″ N, 118°25′63″ E). Seven treatments were implemented with three replicates each: CK (chemical fertilizer only), AB (20 t·ha$^{-1}$ biochar), M1 (7.5 t·ha$^{-1}$ manure), M2 (15 t·ha$^{-1}$ manure), ABM1 (AB + M1), ABM2 (AB + M2), and 2ABM1 (double AB + M1). Soil aggregates were separated by wet-sieving into three size fractions (2–0.25 mm, 0.25–0.053 mm, and <0.053 mm). Humic substances were fractionated into humic acid (HA), fulvic acid (FA), and humin (HU), and their chemical structures were analyzed using Fourier transform infrared spectroscopy (FTIR).

(1) Analysis of the content of humic substance components indicated that the addition of biochar and cattle manure enhanced the levels of humic fractions within soil aggregates. Treatments receiving biochar and/or manure showed higher organic carbon contents of HA, FA, and HU compared to other treatments. In the 2–0.25 mm aggregate fraction of the ABM2 treatment, HA, FA, and HU increased by 45.73%, 41.26%, and 24.09%, respectively, relative to the control. Corresponding increases in the 0.25–0.053 mm fraction were 44.06%, 34.90%, and 35.03%, while in the <0.053 mm fraction, increases reached 56.38%, 120.31%, and 63.82%, respectively.

(2) FTIR analysis revealed that in the 2–0.25 mm fraction, the application of biochar and manure increased the relative contents of aliphatic, aromatic, and polysaccharide compounds in HA and HU, as well as aliphatic and aromatic components in FA. In the 0.25–0.053 mm fraction, both amendments enhanced the relative contents of aliphatic, aromatic, and polysaccharide substances in HA, and increased aliphatic and aromatic components in FA for both soils studied. In the <0.053 mm fraction, biochar and manure application raised the relative contents of aliphatic and aromatic groups in HA but decreased those in FA.

**Acknowledgments**

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# The influence of the application of sewage sludge compost on the yield of winter oilseed rape

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**ABSTRACT**

The decline in the content of organic matter in the soils of Vojvodina (the northern part of the Republic of Serbia) represents their most important degradation process. In the absence of organic fertilizers for the soil, the application of various industrial composts is considered as a possible solution to stop this degradation process.

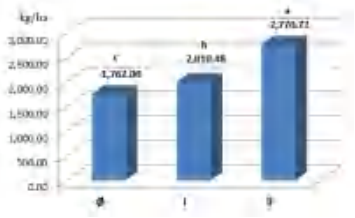
Disposal of sewage sludge in municipal waste landfills is the least favorable option for several reasons (occupation of the capacity of the landfill itself and loss of valuable organic substances found in the sludge). The composting process at the Regional landfill begins with the mixing of sludge created by the purification of wastewater from the city of Subotica and shredded green waste (wooden biomass) collected from public city areas. Compost material goes through a mesophilic phase (25-45 C°), a thermophilic phase (up to 65 C°, with turning and aeration), cooling phase and ripening phase. The tested compost has > 30% organic matter and is free of dangerous and harmful substances.

An agricultural soil of the chernozem type, locality Bikovo, in the area of the Subotica Regional Landfill (N 45°58'37", E 19°47'54") was sampled and tested. All examined soil properties exhibited values typical of this soil type.

An experiment with three variants (Ø – without added compost, I - with 7.5 t/ha of added and plowed compost and II - with 15 t/ha of added and plowed compost) was set up on the plot in four repetitions.

The winter oilseed rape variety Zlatna (group “00”) was used in the trial. Throughout the vegetation period, the plants remained in good condition, with vigorous growth and timely advancement through all phenological stages.

Harvesting was done with a plot combine harvester ZÜRN 150.



Graph 1. Rapeseed yield by varieties of applied compost

The yield of rapeseed on variant II was statistically significantly higher (at the significance level of 0.05) compared to variant I and the control variant (without compost application). Also, the yield of rapeseed on variant I was statistically significantly higher compared to the control variant (graph 1). These differences can be explained by the introduction of nitrogen into the soil originating from the compost, as well as by the partial mineralization of organic matter from the compost.

These results of the experiment indicate the importance of applying compost as a source of nitrogen, which is the bearer of yield. Given that these are one-year data, it is necessary to continue the experiment in the following period.

**Acknowledgments**

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# The soil rhizosphere metabolome's regulating mechanism on microbial communities depending on straw application depths

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**ABSTRACT**

Rhizosphere metabolites are key drivers in shaping microbial community structure and function. They mostly consist of small-molecule compounds under straw return conditions, such as microbial metabolites, straw degradation products, and root exudates, which act as critical signals and energy sources for soil biochemical processes. The rhizosphere metabolome is influenced by the significantly different soil conditions created by different straw return depths, however it is still unknown how the rhizosphere metabolome regulates microbial communities. In order to examine the regulatory mechanisms of the soil rhizosphere metabolome on microbial communities under varying straw return depths, this study designed a field experiment with four different straw return depths (straw removal, surface mulching, shallow return, and deep return) in combination with 16S rRNA amplicon sequencing and LC-MS/MS untargeted metabolomics. The results showed that the number of rhizosphere soil metabolites was greatly increased by straw return, with surface mulching > deep return > shallow return, reaching 147, 119, and 114 species, respectively. Furthermore, surface mulching increased benzenoids, lipids, and lipid-like metabolites in comparison to straw removal; shallow return increased metabolites of organic heterocyclic compounds; and deep return mainly increased metabolite abundance rather than diversity. Additionally, under varying straw return depths, metabolites may control the composition and abundance of microbial communities, with Actinobacteria and Bacteroidetes dominating surface mulching, Actinobacteria and Gemmatimonadota dominating shallow return, and deep return microbial communities showing increased abundance across phyla under metabolite influence. In conclusion, surface mulching showed the strongest regulating effect with respect to alterations in rhizosphere soil metabolites and microbial populations. This study provides a theoretical basis for understanding rhizosphere microbial activity and improving soil environments.

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# Revitalizing Sandy Soils: Organo-Mineral Inputs Enhance Drought Resilience in Wheat and Microbes

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**ABSTRACT**

Increasing drought conditions severely limit nutrient cycling and wheat production in sandy soils. Organic and mineral amendments such as compost (CM), sheep manure (SM), and bentonite clay (BN) have potential to improve drought resilience. Research on how different rates and types of organo-mineral amendments affect wheat and microbial drought resilience in sandy soils remains limited. We aimed to understand how CM, SM, and BN interact to improve wheat drought resilience in four experiments. **In Experiment I,** three drought-sensitive wheat varieties (Trojan, Cobra, and Gregory) were screened under five drought levels. Based on aboveground and belowground traits, and soil nutrient levels, Trojan, the best performer under drought, was selected for Experiment II. **In Experiment II,** organic amelioration of drought was assessed using CM or SM at three application rates (10, 25, or 40 g $kg^{-1}$) at 75%, 50%, and 25% of water holding capacity (WHC). Under drought (25% and 50%WHC), CM and SM at 25 g $kg^{-1}$ had greatest increase in aboveground (20%), belowground (70%) biomass and photosynthetic rate (42%), but decreased specific root length (34%), relative to the unamended control. Across water levels, CM and SM increased N and P uptake, $NO_3^-$-N, available P, microbial biomass N (MBN) and P (MBP), whilst decreased $NH_4^+$-N and mineral N, with greater effect at 25 g $kg^{-1}$. **In Experiment III,** moderate rate (25 g $kg^{-1}$, eq. 37.5 t $ha^{-1}$) of CM and SM alone (100%CM, 100%SM) or combined (50%CM+50%SM) was applied to assess wheat yield and soil water retention at 75% and 35%WHC during critical vegetative and reproductive growth stages. At 35%WHC, 100%CM and 50%CM+50%SM showed greater increase in yield and physiology during vegetative than reproductive stage. Generally, N uptake, $NO_3^-$-N, and MBN were greater with 100%CM, P uptake, available P, and MBN with 100%SM, and moisture retention and plant available water with 100%SM and 50%CM+50%SM, relative to control. **In Experiment IV,** individual and combined effects of micronized (< 1µm) SM (25 g $kg^{-1}$) and BN (3% w/w) were investigated on soil moisture dynamics, rhizosphere microbial communities, and wheat productivity under 75% and 25%WHC. Synchrotron micro-CT analysis used to visualize and quantify amendment-induced changes in soil porosity and microstructure. We hypothesize that amendment-driven increase in microporosity will enhance water retention in sandy soil, particularly at 35%WHC, leading to improved nutrient availability, microbial activity, and wheat yield. Overall, CM-, SM-, and BN-induced wheat drought resilience was likely due to improved nutrient availability, enhanced water retention capacity, and stimulation of microbial activity in the sandy soil. The moderate rate (25 g $kg^{-1}$, eq. 37.5 t $ha^{-1}$) of CM and SM, alone or combined with BN, could substantially mitigate the negative effects of drought on wheat production, nutrient cycling, moisture retention and microbial dynamics in sandy soils.

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# Optimizing Soil Fertilization Processes for Improving 4R Nutrient Stewardship

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**ABSTRACT**

4R (right rate, right source, right time, right place) Nutrient Stewardship boosts farming profitability and reduces environmental concerns. The current 4R practices were developed using commercial chemical fertilizers (CCF) under field conditions. However, cropping systems that use manure have different management needs than those that use CCF. In manure-intensive regions such as southwest Ontario, manure amendments introduce organic N fractions that may not fully mineralize in the year of application, creating legacy N fertility effects that complicate fertilizer decision-making. Soil texture further influences N availability through its effects on organic matter stabilization, microbial activity, and water retention, yet the combined impacts of manure type, manure form, residual N, and soil texture remain poorly quantified under Ontario conditions. To address the critical research gaps, this study evaluated the first year and residual N availability of pig and cattle manures (solid and liquid forms) compared with CCF across contrasting soil textures. A controlled greenhouse pot experiment using ryegrass was conducted with sandy loam and clay loam soils collected from Essex County, Ontario, followed by calibration and validation under long-term corn–soybean rotation field conditions. Treatments included five N amendments (i.e. chemical fertilizer, solid and liquid pig and cattle manures) applied at four N rates (i.e. zero-N, 0.7×RNR, 1.0×RNR, and 1.3×RNR). The first year and residual N availability of N amendments were calculated using the zero-N treatment as a control. Plant samples were digested after two harvests, and plant biomass, N uptake, nutrient use efficiency (NUE), and soil N and P dynamics were assessed across multiple cuts. Results showed that chemical fertilizers initially increased crop yield and prompted early biomass production compared with manure-based treatments. Solid and composted manures released nutrients slowly and improved nutrient retention, but liquid manures increased biomass production quickly, particularly in sand-textured soils. These findings show that optimal manure management can improve NUE while supporting soil nutrient management, providing insights for integrating organic amendments into 4R nutrient stewardship frameworks.

# Nutrient enriched biochar reduces chemical fertiliser requirements for forestry seedling growth

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## ABSTRACT

Nutrient-enriched biochar (NEB) offers a way to turn forestry residues and dairy effluent into a valuable fertiliser product that supports a circular nutrient economy, but its optimal use for plantation seedlings is not yet well understood. This study tested NEB for Eucalyptus nitens seedlings in both a controlled pot trial and a replicated field trial on a Red Ferrosol in Tasmania, Australia. NEB was produced by soaking hardwood timber-residue biochar in dairy effluent washdown liquid and applied either alone at two rates, or in combination with a slow-release mineral fertiliser, alongside an industry-standard fertiliser treatment and an unfertilized control. In the glasshouse, after 140 days, seedlings receiving NEB plus fertiliser or fertiliser alone showed significantly greater stem diameter, shoot biomass, leaf number and branch number compared to the control, whereas NEB on its own did not enhance growth. Similar results were observed in the field, where seedlings receiving NEB plus fertiliser or fertiliser alone were 40 % taller (approx. 0.5 m) than the control after 13 months, again with NEB alone unable to match this growth response. Before transplanting, the NEB–fertiliser mix delivered the same initial ammonium-nitrogen supply as the industry-standard fertiliser despite containing only half the total nitrogen and both treatments slightly increased soil pH. NEB treatments also boosted available potassium and several micronutrients, including boron, zinc and manganese. These initial differences in soil ammonium, potassium and pH were no longer evident after 140 days of seedling growth, indicating active nutrient uptake and redistribution in the system. Overall, NEB, when combined with mineral fertiliser, was able to sustain seedling performance comparable to the industry standard while partially substituting for mineral nitrogen and potassium and contributing useful micronutrients, without negatively affecting soil properties. These findings suggest that NEB can function as a supplementary nutrient source rather than a complete fertiliser replacement for forestry seedlings. Future work should explore higher dairy effluent loadings during NEB production and longer-term trials over 5–15 years to determine whether NEB can reliably support plantation establishment and early growth as part of an integrated fertiliser strategy.

**Acknowledgments**

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# Organic Waste Recycling in paddy:Enhancing Soil Health and Crop Quality - A case in Suzhou

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**ABSTRACT**

The resource utilization of organic waste is a crucial pathway for promoting the green transformation of agriculture and synergistically enhancing soil health and the sustainable production capacity of rice.This study presents the results of a long-term field experiment initiated in 2018,focusing on the sustainable recycling of organic waste in typical paddy systems of Suzhou.Through multi-dimensional evaluations,it systematically investigates and assesses the long-term comprehensive effects of applying kitchen waste compost and similar organic amendments on soil health (encompassing physicochemical properties,microbial diversity,biodiversity,and ecosystem functions),as well as on rice yield,quality,and economic viability.The key results are summarized as follows:

(1)Significant improvement in soil physicochemical properties:The application of kitchen waste compost significantly increased soil organic matter content (by up to 18.52%),available nitrogen,phosphorus,and potassium,stabilized soil pH,reduced bulk density and enhanced aggregate stability.The secondary compost treatment showed particularly notable effects,improving aggregate water stability by approximately 19.2–49.3% and markedly optimizing soil structure.

(2)Enhanced soil carbon sequestration capacity:The kitchen waste compost treatment promoted the accumulation of both active and inert organic carbon,particularly increasing carbon storage in the topsoil (0–20 cm) and raising the proportion of mineral-associated organic carbon,contributing to the formation of a stable carbon pool and enhancing long-term soil carbon sequestration potential.

(3)Improved soil microbial diversity and functionality:Long-term application of kitchen waste compost significantly increased soil bacterial α-diversity (e.g.,elevated Shannon index) and enriched beneficial functional microbial communities (such as nitrogen-fixing and organic matter-degrading bacteria).It also enhanced the activity of key soil enzymes,including dehydrogenase and β-glucosidase,thereby strengthening nutrient cycling and pollutant degradation capacity.

(4)Enhanced paddy biodiversity and ecological functions:Organic farming practices helped maintain the stability of weed communities in paddy fields,significantly increased the diversity and niche breadth of natural enemies such as spiders,and improved the natural control of pests like rice planthoppers, promoting the balance of the farmland ecosystem.

(5)Synergistic improvement in rice yield, quality, and economic benefits: Under the premise of ensuring food security, the kitchen waste compost treatment increased rice yield by 0.8–56.9% compared to conventional chemical fertilizer treatments. From an economic perspective, optimized organic rice systems demonstrated a higher net economic value, exceeding conventional rice by up to 5,399.45 CNY/hm².Ecological subsidy policies,such as crop rotation and fallow incentives,further improved economic profitability by approximately 2.7%.Additionally, farmer willingness-to-accept (WTA) compensation for ecological rice cultivation reached up to 14,000 CNY/hm²,indicating strong potential for economic viability and farmer adoption. Importantly, rice quality in terms of taste and appearance met premium standards without introducing heavy metal or salinity risks, achieving multiple objectives of "increased yield, improved quality,and enhanced economic sustainability".

This study confirms that implementing organic waste recycling in Suzhou's paddy systems can synergistically improve soil health through multiple pathways—"physicochemical properties,microorganisms,and biodiversity"—while simultaneously enhancing rice yield and quality.It provides a scientific basis for green rice production and circular agricultural practices in the region.

**Key Words:** Organic waste recycling;Paddy field;Soil health;Kitchen waste compost;Long-term field experiment

# Different parts of corn plant residue returning to field caused the differences of humus composition in quantity and humic acid in molecular level in black soil

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**ABSTRACT**

Purpose: The objective of this study was to determine how residues from different anatomical parts of the corn plant affect SOC content and the molecular structure of humic acid (HA) in black soil, using long-term incubation and advanced spectroscopic techniques.The study provides new insights into how targeted residue management based on plant anatomy can be leveraged to optimize soil fertility and carbon sequestration strategies in sustainable agriculture.

Methods: This experiment selected 7 different parts of corn plant residues as experimental materials for pot experiments. Through FTIR, Fluorescence spectra and $^{13}C$ CPMAS NMR technology, the changes and characteristics of the ingredient and structure of HA were qualitatively characterized.

Results: The results show that the application of corn plant residues can increase the SOC content and the proportion of humus, Compared with 360d, after 720d of cultivation, the soil organic carbon content in each treatment increased to varying degrees. And compared to CK, the R treatment showed the highest increase in PQ value at 6.45%, while the PB treatment exhibited the smallest increase at 2.67%. The elemental composition and $^{13}C$ CPMAS NMR results demonstrated that the application of corn plant residues enhanced the ratio of H/C and the aliphatic C/aromatic C ratio of HA and reduced the O/C ratio, indicating enhance the aliphaticity of soil HA, reduce the oxidation degree and condensation degree, and rendered HA molecular structure simpler.

Conclusion: The higher the carbon content between different parts of the residues, the more plant parts containing difficult to decompose components (such as lignin and carbon with alkyl structure), the higher the degree of humification. The residues from root and stem bark significantly enhanced humification, promoted the formation of more aliphatic and stable HA structures, and contributed more effectively to SOC buildup compared to leaf and bract residues.

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# Organic compounds in organically managed farmland in Fukushima and their effects on roots of A. thaliana

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## ABSTRACT

Topsoil removal in the Fukushima Prefecture as response to the radioactive contamination through the Fukushima Daiichi nuclear power plant incident in 2011 led to severely impacted soil. In response, the restoration of the crop soil layer is an important undertaking. The prime focus for the restoration of the soil is the organic content.

In this study, we analyzed the content of soluble organic compounds present in the soil solution of an organically managed field in the Fukushima Prefecture by Liquid Chromatography - Orbitrap mass analysis. We identified several organic acids and amino acids that are abundant in the soil solution samples, and potentially available to plants.

We chose the 10 most abundant organic compounds to test the influence on A. thaliana root growth. Instead of applying high concentrations, we focused on a concentration range that is most commonly associated with High Affinity Transport Systems (HATS). The tested concentrations were mainly in the µM range, with the highest concentration being 1 mM. All tested concentrations were added in addition to MGRL media to see effects that are prominent while the plants have a good nutritional status (as it should be in agricultural applications).

We were able to classify the organic compounds into either no alteration of growth, growth suppression and growth promoting, based on root length, shoot weight and additional photosynthetic measurements. Currently RNA sequencing is ongoing to identify genes responsible for this regulation.

The aim of this study is to identify which organic compounds are released in organically managed fields, that are available to crops. Further, we will develop plants that are better adapted towards growth in these conditions.

# Beyond Porosity: Dual-Mode Nitrogen Fertilizers from Metal-Modified Biochar

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**ABSTRACT**

Nitrogen leaching and volatilization represent major challenges in the development of efficient fertilizer. In this work, we explore the development of a chemically modified sawdust biochar able to sorb Green Ammonia (John et al., 2023), aiming at the production of slow-release fertilizers. Biochars were modified with several metals (Mn, Zn, Fe) reaching an increase of up to 65% in nitrogen content compared to the pristine biochar, highlighting the dominance of surface chemistry over pore structure in ammonia retention. To explain the increase in N%, several characterization techniques (XPS, XRD, FT-IR, SEM-EDS) were performed in order to obtain a mechanistic understanding of the sorption process. XPS and XRD revealed a pivotal role of the metals in the sorption process, indicating that ammonia retention is not limited to classical ionic interaction, but involves the formation of crystalline ammonia complexes on the biochar surface. The obtained fertilizers show a dual modal release that combines the fast release typical of physisorption with the slow release obtained by the formation of amidic bonds. These fertilizers show an increase in slow-release ammonia compared to the pristine biochar, reaching 50% of covalently bonded ammonia. Moreover, the selection of the metals was not fortuitous, all those metals are also micronutrients for the plants, enabling the simultaneous delivery of two pivotal elements. This approach lays the basis for a future creation of an “in situ” small implant for the production of fertilizers that allow a fast release before the sowing and a controlled release during the growth.

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# Banana growers: Battling with soils for productivity in the Chitwan valley of Nepal

**ABSTRACT**

With the realization that soils of the Chitwan Valley (180 m - 220 m amsl) of Nepal are fertile and resourceful, the government promoted a policy to provide sizeable financial and technical support to the banana growers after the district was categorized as a super-zone (>1000 ha cultivation) of banana. The zonal concept was introduced under the Prime Minister's Agriculture Modernization Project in 2016. After the declaration of the super-zone, the government assumes that agriculture production should be increased in a self-sufficient manner. Paradoxically, a recent transect survey of three banana (dominated by G9 var.) farms from the Padampur, Jagatpur, and Tribeni areas in the East-Rapti River corridor of the Chitwan district revealed that much of the scientific data needed for soil improvement required for commercial production of bananas is lacking. During the survey, farmers reported that their banana super-zones increasingly face soil health challenges mainly due to soil acidity, excessive use of chemicals and pesticides, decreased groundwater tables for irrigation, reduced organic matter, and nutrient depletion in soil. This has resulted in declining banana productivity (approx. 20 Mt to <15 Mt/ha) with time. Over 600 banana growers (registered and unregistered, combined) are likely to suffer from these drivers of soil degradation in the district. Worthy of mention is one example: widespread 'Panama disease' could be suppressed by judicious liming of soils, but it must be verified by farmers' field experimentation. It implies that such investigations should be tailored to the need for periodic soil tests for fertilizer recommendation, residue management, bio-fertilizer promoting healthy soil ecosystems, and assessing lime requirements to bring soil to a desired acidity level. Most farmers have benefited from government subsidies; many are still missing out due to unclear land-use policy hampering the good soil management practices for optimization of banana production in the region. In summary, this quick field survey suggests that while government efforts are somewhat visible, more emphasis should be laid onto integrated nutrient management involving banana farmers and field-based research outcomes.

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# In-Vessel Composting of Poultry Litter with Lignite Granules: A Strategy for Emission Mitigation

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## ABSTRACT

The management of poultry litter presents a significant environmental challenge due to its high nitrogen content and the risk of gaseous emissions. The composting of poultry litter is a widely recognized organic waste management strategy. However, it is often associated with significant gaseous emissions, including ammonia ($NH_3$), greenhouse gases (GHGs) such as methane ($CH_4$) and nitrous oxide ($N_2O$), and odorous components including volatile organic compounds (VOCs) and hydrogen sulfide ($H_2S$). These emissions contribute to nitrogen loss, environmental pollution, and public health concerns. While previous studies have focused on nutrient retention and GHG mitigation in the composting process, limited research has comprehensively examined odour reduction, which remains a critical concern for farmers. The unpleasant odour generated during composting is a major barrier to its widespread adoption, making odour control an essential aspect of sustainable manure management. This study investigates the potential of lignite granules, a low-rank coal derived carbonous product, as an additive to mitigate gaseous emissions during in-vessel composting of poultry litter. A series of closed laboratory composting reactors were used, each containing 30 L of composting material. Treatments included control (no lignite addition) and different dosages of lignite in both powdered and granulated forms to evaluate their comparative effects. Gas emissions ($NH_3$, $CH_4$, $N_2O$, VOCs, and $H_2S$) were monitored throughout the composting process using advanced analytical instruments, including a Picarro G2508 gas analyzer for $NH_3$ and GHGs, and GC-MS for VOC quantification. Additionally, compost quality parameters such as pH, moisture content, total nitrogen, and carbon retention were assessed to determine lignite's impact on nutrient stabilization.

Preliminary projections based on lignite's physicochemical properties suggest that its addition reduces $NH_3$ emissions by adsorbing ammonium ions and stabilizing nitrogen within the compost matrix. Similarly, its porous structure facilitates VOC and $H_2S$ adsorption, leading to reduced odour emissions. The presence of lignite may also influence microbial activity, potentially modulating $CH_4$, $N_2O$ emissions. Comparative analysis between powdered and granulated lignite highlights the most effective formulation for practical applications.

The findings of this study provide valuable insights into the feasibility of using lignite granules as a sustainable solution for emission control in poultry litter composting. If successful, this approach could enhance compost quality, reduce environmental pollution, and support the broader adoption of composting technology in poultry farming. Future research will focus on scaling up the application of lignite in semi-commercial composting systems and evaluating its long-term agronomic benefits.

**Keywords:** Poultry litter, Lignite granules, Ammonia mitigation, Greenhouse gases, Odour control, Compost quality.

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# Closing the Loop in Agriculture: Biochar for Soil Restoration and Productivity

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**ABSTRACT**

Agricultural production is increasingly constrained by soil degradation, climate change, and the inefficient management of organic residues, while conventional linear farming systems continue to accelerate soil resource depletion and environmental pollution. This presentation introduces biochar-based circular agriculture as an integrated and soil-centered approach to addressing these challenges. It first frames circular agriculture within the context of global agricultural pressures, with particular emphasis on critical soil problems including salinity, acid sulfate soils, land degradation, and desertification, as well as current limitations in managing organic residues from agricultural production. The conversion of these residues into biochar is then presented as a value-added pathway that transforms agricultural waste into a stable, carbon-rich soil amendment. Studies show that biochar can effectively improve soil acidity regulation and nutrient-related properties, with reported improvements in soil pH balance, nutrient retention, and overall fertility commonly reaching 30–50%, depending on soil conditions and biochar characteristics. In contrast, its effects on soil salinity remain inconsistent and highly context-dependent, indicating that biochar does not provide a universal solution to salinity stress. Crop yield responses are therefore shown to depend primarily on the extent to which biochar alleviates dominant soil constraints and matches crop-specific nutrient demands, rather than on biochar application per se. The presentation concludes by proposing a conceptual model of biochar-based circular agriculture that integrates residue recycling, soil restoration, yield improvement, and climate mitigation, positioning biochar not as a standalone yield-enhancing input but as a soil-function-oriented amendment for building healthier and more resilient agricultural systems.

**Key words:** Biochar, Circular agriculture, Soil health, Organic residues, Crop productivity

# Biochar Utilization Strategies Based on Feedstock and Application Frequency: Effects of Wood and Chicken Manure Biochars on Crop Productivity

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## ABSTRACT

Biochar has been promoted as a soil amendment to enhance soil carbon sequestration and mitigate greenhouse gas emissions. However, biochars derived from different feedstocks exhibit substantial variation in carbon structure and inorganic nutrient composition, which may result in contrasting agronomic functions. In particular, manure-derived biochars with high ash and nutrient contents may act more as nutrient sources than contribute to carbon sequestration, raising questions regarding their sustainable use in agricultural soils. This study evaluated the effects of wood biochar (WB) and chicken manure biochar (CB) on crop yield under contrasting soil fertility conditions.

A two-year field experiment was conducted at two sites: a low-fertility upland soil cultivated with soybean and a high-fertility greenhouse soil cultivated with red pepper. WB and CB were applied at rates of 0, 1, 2, and 4 Mg $ha^{-1}$. To distinguish residual and cumulative effects, each plot was divided into one-year application followed by one-year residual effect (1/2y) and two consecutive applications (2/2y). Physicochemical characterization showed that WB had a well-developed carbon structure with high specific surface area (213 $m^2$ $g^{-1}$) and porosity (0.1295 $cm^3$ $g^{-1}$), whereas CB exhibited low porosity (0.0116 $cm^3$ $g^{-1}$) but contained high concentrations of available inorganic nutrients (citrate-soluble $P_2O_5$: 2.4%, water-soluble $K_2O$: 3.2%) and high electrical conductivity (50.1 dS $m^{-1}$).

Crop yields were evaluated after the second year. In the low-fertility soybean field, the optimum application rate of WB shifted to lower with increasing application frequency (1/2y: 1.83 Mg $ha^{-1}$, 2/2y: 1.06 Mg $ha^{-1}$). In contrast, CB considerably increased soybean yield with increasing application rate, and yield responses were further enhanced under the 2/2y treatment (4-1/2y: 2.9 Mg $ha^{-1}$, 4-2/2y: 4.1 Mg $ha^{-1}$), indicating a strong cumulative fertilizer effect. In the high-fertility red pepper greenhouse, WB showed an optimum application rate of 1-2 Mg $ha^{-1}$ under both application frequencies. CB increased red pepper yield with increasing application rate under the 1/2y treatment (1-1/2y: 5.1 Mg $ha^{-1}$, 4-1/2y: 5.9 Mg $ha^{-1}$); however, under consecutive application (2/2y), yield decreased with increasing application rate (1-2/2y: 6.6 Mg $ha^{-1}$, 4-2/2y: 5.7 Mg $ha^{-1}$). These results suggest potential stress effects related to nutrient accumulation or salinity.

Overall, WB might function as a buffering carbon-based amendment with indirect effects on crop yield, whereas CB acted as a nutrient-rich fertilizer whose agronomic benefits and risks depended on soil fertility and application frequency. These findings emphasize the need for feedstock-specific management strategies for the sustainable use of organic waste-derived biochars in soil fertility management.

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# Impacts of Applications of Three Wood Ash Types on Elemental Dynamics and Crop Growth

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**ABSTRACT**

Wood biomass combustion ash (wood ash) has high potassium (K) content, and its reuse as a fertilizer has attracted increasing interest in response to rising fertilizer prices. However, some types of wood ash also contain heavy metals such as Cr, and the behavior of heavy metals in soil after wood ash application remains insufficiently understood. This study aimed to characterize the physicochemical properties of different wood ashes and to evaluate their effects on elemental dynamics in soil solution and crop growth.

Three types of wood ash (A, B, and C) were characterized using X-ray diffraction (XRD), scanning electron microscopy with energy-dispersive spectroscopy (SEM–EDS) and titration test. Chromium speciation in wood ash A was further examined by X-ray absorption near-edge structure (XANES) analysis. A pot experiment was conducted using K-deficient Gray Lowland soil. Komatsuna (*Brassica rapa var. perviridis*) was grown with the application of ammonium sulfate (N: 100 mg), superphosphate ($P_2O_5$: 100 mg) and 1% wood ash. The treatments used NP and NPK fertilizer were conducted as control. Soil solution was collected during cultivation, above-ground dry biomass and elemental concentration in crops was determined following acid digestion and ICP–OES analysis.

The results showed that all wood ash contained abundant carbonate minerals and exhibited strong buffering capacity. XANES analysis indicated that Cr in the wood ash was present as 33% Cr(VI) and 67% Cr(III). Compared with NP treatment, all wood ash treatments increased K concentrations in both soil solution and crops, resulting in a 1.33–1.90-fold increase in above-ground dry biomass, demonstrating the effectiveness of wood ash as a K fertilizer. Concentrations of Cd and Zn in soil solution and crops decreased, with Cd levels reduced to below the Codex limit for leafy vegetables (0.2 mg $kg^{-1}$). The reductions in Cd and Zn were attributable to increased soil pH, which enhanced cation adsorption onto soil particles and promoted precipitation reactions. Although Cu and Cr concentrations increased in soil solution, their concentrations in crops decreased. This trend is consistent with a recent study by the authors (2025), which demonstrated that Cu and Cr form stable complexes with dissolved organic carbon at higher pH, thereby reducing their bioavailability to crops.

This research was supported by the Research and implementation promotion program through open innovation grants (JPJ011937) from the Project of the Bio-oriented Technology Research Advancement Institution (BRAIN). This work was also supported by the Project of Integrated Compost Science (PICS).

# From Waste to Resource: Stabilizing Nitrogen in Broiler Litter Using Granulated Lignite

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**ABSTRACT**

The sustainable management of global nutrient cycles is central to the congress theme *Advances in Soil Fertility Management Through the Utilization of Organic Waste*. As global population growth intensifies pressure on food systems, maintaining a livable planet will depend on improving the recovery and reuse of carbon and nutrients from organic waste streams. It is estimated that 2.6 million tonnes of organic waste are generated globally each day, accounting for over 40% of total waste by mass (ISWA, 2020). Rich in organic carbon and essential plant nutrients, these materials represent a critical opportunity to enhance soil health and build climate-resilient cropping systems.

In intensive animal production systems such as broiler housing, more than half of the nitrogen (N) excreted by birds can be lost prior to waste collection, primarily through ammonia ($NH_3$) volatilization. These losses reduce the nutrient density, economic value, and fertilizer potential of broiler litter. In addition, land application of untreated litter can contribute to environmental nitrogen losses via leaching and surface runoff. Stabilizing N in broiler litter is therefore a key prerequisite for developing a circular agricultural waste economy.

Lignite, an abundant and low-cost brown coal resource in south-eastern Australia, has emerged as a promising amendment for sustainable organic waste management. When incorporated into broiler bedding, lignite reduces $NH_3$ volatilization, suppresses microbial activity, slows litter decomposition, and lowers odor emissions. However, conventional run-of-mine lignite is high in moisture content, dusty, bulky, and difficult to distribute, limiting commercial adoption. To overcome these constraints, a granulated lignite formulation has been developed for practical on-farm application.

This presentation reports commercial-scale testing of a lignite granule in broiler housing, compared with powdered lignite and a no-lignite control. We quantify the impact and elucidate the mechanisms underpinning N stabilization in lignite-fortified broiler litter using various techniques ($^{15}N$ tracer, $NH_3$ and greenhouse gas fluxes via Picarro G2509, odor via olfactometry). Results demonstrate enhanced nutrient retention, reduced mass loss and odor emissions, and improved litter quality relative to conventional management. Overall, lignite-fortified waste streams provide a superior feedstock for high-value organo-mineral fertilizers, supporting improved nutrient use efficiency, soil health, and climate-resilient agriculture.

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# Regulation of Humification and Nitrogen Retention during Organic Waste Composting by Compound Microbial Agents

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**ABSTRACT**

Compost application of organic waste to soil is an important approach to achieve resource recycling and improve soil fertility. However, low humification efficiency and severe nitrogen loss remain key bottlenecks restricting its high-efficiency utilization. This study used food waste and crop straw as typical raw materials, focusing on the key mechanisms and technical optimization of humification regulation by compound microbial agents, and established an integrated technical system of "raw material pretreatment - targeted inoculation of functional agents - precise regulation of composting process". Through screening brown-rot fungi (BRF) and cellulolytic nitrogen-fixing bacteria (CNFB) to construct a high-efficiency compound microbial community, the effects of key parameters such as microbial agent ratio and carbon-to-nitrogen (C/N) ratio on compost humification process and nitrogen retention efficiency were systematically investigated. Combined with three-dimensional excitation-emission matrix fluorescence spectroscopy (3D-EEM) and functional gene sequencing technologies, the microscopic regulatory mechanisms of the compound microbial agent in promoting Maillard/polyphenol humification pathways and inhibiting denitrification were clarified.

The results showed that the compound microbial agent with optimized ratio could extend the high-temperature phase of composting by 3-4 days and significantly enhance the humification process: the content of humic acid (HA) in the compost product increased by more than 30%, and the humification index (HA/FA) reached above 6.2. Meanwhile, it effectively inhibited nitrogen loss by 20% and increased the available phosphorus content by 15%-25%. Verification by field plot experiments showed that after applying the compost product to farmland, it could significantly improve soil aggregate structure, enhance soil microbial community activity, and promote the absorption of nitrogen and phosphorus nutrients by crops, with the absorption efficiency increased by 12%-18% respectively.

Through the enhancement of microbial functional synergy, this study achieved the organic integration of efficient resource transformation of organic waste and enhancement of soil fertility. The constructed technical process is simple, controllable and easy for short-term transformation, providing a precise technical scheme for the local return of agricultural organic waste to the field and the reduction and substitution of chemical fertilizers. It is of great significance for promoting green and sustainable agricultural development and ensuring soil ecological security.

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# Soil Nutrient Management in Oil Palm Plantation: The Application of Palm Oil Mill Effluent (POME) for Sustainable Agriculture

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**ABSTRACT**

Palm Oil Mill Effluent (POME) is an organic liquid effluent generated during the production of Crude Palm Oil (CPO) and Palm Kernel Oil (PKO) in a Palm Oil Mill. In oil palm plantations, POME is applied to the plantation and is able to fully substitute for synthetic fertilizer. This study aimed to compare plant and soil nutrient contents in oil palm plantations with and without the application of POME. The research was conducted on an oil palm plantation on mineral soils in Paser Regency, East Kalimantan, Indonesia, using two treatments: blocks treated with POME (8 blocks) and blocks without POME (8 blocks), where synthetic fertilizers served as the primary nutrient source. Each block covered 30 hectares and had a planting density of 136 trees per hectare, comprising palms planted in 2008 and 2009. Leaf nutrient contents (N, P, K, Ca, Mg) were analyzed annually in 2018, 2019, 2020, 2022, and 2023, while soil analyses were conducted in 2017 and 2022. The nutrient content of POME (pH, P, K, Ca, and Mg) was also analyzed in the laboratory, after the sample was collected from the Contact Pond. Statistical analyses were performed using t-tests or Wilcoxon tests for non-normally distributed data. Results showed that leaf nutrient content in 16- and 17-year-old palms, both with and without POME application, remained within the optimum range. No significant differences were observed in leaf N, K, and Mg contents in 17-year-old palms, nor in soil nutrient status, with acidic soil pH values of 4.58–5.34 and organic carbon contents ranging from 0.80–1.20%. Similarly, in 16-year-old palms, leaf nutrient contents (N, P, K, Ca, Mg) remained optimum with no significant differences between treatments. Soil pH in both treatments was acidic (4.55–5.33), with organic carbon contents of 1.03–1.55%. However, Ca and Mg levels were higher in soils treated with synthetic fertilizers, likely due to the application of dolomite. The nutrient analysis of POME indicates a very high available nutrient content, with available P at 469 ppm and exchangeable K and Ca at 1506 ppm and 149 ppm, respectively. Meanwhile, the pH of POME discharged into palm oil plantations is 8.78. These findings demonstrate that the application of POME in oil palm plantations promotes circular agricultural practices, reduces reliance on synthetic fertilizers, and mitigates greenhouse gas emissions, thereby contributing to sustainable agriculture.

***Keywords:*** *biofertilizer,fertilizers, nutrient recycle, organic*

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# FUNGAL CONSORTIUM ASSISTED COMPOSTING FOR RAPID STABILIZATION OF POULTRY LITTER

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**ABSTRACT**

The rapid expansion of the poultry industry has led to the continuous accumulation of poultry litter, a heterogeneous organic residue composed primarily of manure, bedding materials and feed remnants. Inadequate management or disposal of this waste stream can result in nutrient leaching, offensive odour generation and greenhouse gas emissions, thereby posing significant environmental and public health concerns. Aerobic composting is widely regarded as a sustainable strategy for stabilizing poultry litter and converting it into a nutrientrich organic amendment; however, the process is often slow and suboptimal because of the structural complexity and recalcitrant nature of the substrate, poultry liiter. The targeted application of microbial consortia as bioinoculants has therefore emerged as a promising approach to accelerate composting dynamics and improve the quality of the final product.In the present study, three fungal isolates, *Trichoderma* sp., *Phanerochaete* sp. and *Pleurotus* sp., were evaluated for their suitability as composting inoculants. Compatibility testing demonstrated that all three isolates were mutually compatible, thereby enabling their formulation as a single fungal consortium. This consortium was incorporated at 3% (v/w) into freshly collected poultry litter and subjected to aerobic composting for 45 days. Moisture content was maintained within the optimal range, and the composting mass was periodically turned to ensure adequate aeration and sustain microbial activity throughout the process.Composting performance and maturity were assessed using a suite of physicochemical maturity indices and bioassay- based indicators. The E4/E6 absorbance ratio decreased from 4.85 in the uninoculated control to 3.32 in the consortiumtreated compost, signifying accelerated humification and more efficient transformation of organic matter. Maize seed germination assays recorded 100% germination in the consortium treatment, compared with 83.33% in the control, indicating a marked reduction in phytotoxicity and enhanced suitability of the compost for plant growth.Furthermore, starch iodine testing confirmed that the inoculated compost retained the light yellow iodine colour, indicating complete polysaccharide degradation, whereas the immature compost developed a brown colour due to residual carbohydrates.Overall, the findings indicate that a fungal consortium comprising *Trichoderma* sp., *Phanerochaete* sp. and *Pleurotus* sp. can substantially accelerate the composting of poultry litter, promote humic substance formation and yield mature, safe compost within 45 days. This bioaugmentation strategy offers considerable potential for the sustainable management and valorization of poultry waste, with broader implications for improving soil fertility, supporting organic fertilizer production and advancing circular bioeconomy frameworks.

**Keywords:** Poultry litter, Aerobic composting, Fungal consortium, Humification, Phytotoxicity

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# Plant Available Nutrient Contributions from Steer Manure Compost in Semi-Arid Agricultural Systems

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## ABSTRACT

The availability of nutrients from steer manure composts (SMC) for crop growth is a complex interaction of soil environment and biogeochemistry with agricultural management. SMC has been used in both irrigated silage maize and dryland organic wheat systems to supply nutrients and improve soil health in long-term experimental plots in the semi-arid environment of northern Utah, USA. These soils are calcareous with high buffering capacities. The irrigated silage maize study was conducted for a decade comparing N fertility sources using a CRB design with four treatments: control with no N fertilizer, ammonium sulfate at 112 kg N $ha^{-1}$(AS112), at 224 kg N $ha^{-1}$ (AS224) and SMC at 224 kg total N $ha^{-1}$. Fertilizer P and K were applied according to preseason soil testing. Silage corn yield, N uptake, N use efficiency (NUE), N cycling and soil health indicators had variable responses across years emphasizing the importance of multi-season studies. Yield under SMC exhibited a notable 41% increase compared to control but was approximately 31% lower than the average yield under AS treatments. AS112 achieved a yield comparable to AS224 and demonstrated higher NUE. SMC significantly enhanced soil total N and soil organic C by 23%. Repeated applications of SMC decreased need for supplemental NPK fertilizers. While AS fertilizers proved effective in achieving higher silage corn yields and NUE compared to compost treatment, SMC enhanced soil C and N and soil health indicators. Our observations highlight interactions between soil C and N and the responsiveness of active organic matter pools and enzyme activities on nutrient supplies. Farmers are encouraged to adopt a balanced approach, incorporating compost alongside fertilizers and implementing soil health practices for sustainable silage corn systems.

In organic dryland wheat systems, yields are limited by irregular rainfall, low soil organic matter, and minimal nutrient availability. A 30-year field study in Snowville, Utah, USA examined the legacy effects of a single large SMC application (50 Mg $ha^{-1}$) applied once in 1994. Persistent improvements in soil fertility and wheat yield were observed over decades, although we still have a limited understanding of the microbial communities driving these benefits. To better understand the mechanisms underlying these persistent benefits, a complementary experiment was established in 2021 to examine the effects of amendments of varying lignin content and C:N ratio: Hardwood Compost, Softwood Compost, SMC and Wheat straw with and without Feather Meal on wheat yields, NPK and microbial communities. Both nutritive and non-nutritive benefits of the SMC were observed in these dryland organic wheat systems. Understanding the longevity of the benefits of composts applications in these resource limited systems is driven by both the biogeochemistry of the composts themselves and the availability of moisture at critical times in the wheat growth cycle.

# Safeguarding global nitrogen sustainability by managing organic waste throughout the food supply chain

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**ABSTRACT**

Organic waste generates substantial nutrient losses and reactive nitrogen ($N_r$) emissions, severely undermining global nitrogen sustainability. However, the specific impacts of various organic waste streams across the full food supply chain (FSC) remain poorly characterized. Here, by integrating a Coupled Human and Natural System (CHANS) model with global FSC datasets, we quantify nutrient losses and $N_r$ emissions from organic waste across 159 countries. Our results show that in 2020, global food loss and waste (FLW) resulted in 34.6 Tg N of $N_r$ emissions and 32.5 Tg N of nutrient losses—equivalent to 29% of total food-system $N_r$ emissions and 43.5% of the global food nutrient supply. Other organic wastes (e.g., crop residues, manure, and sewage) totaled 132.1 Tg N, of which 33.0% was managed inefficiently, contributing an additional 4.8 Tg N to $N_r$ emissions. We find that when accounting for the entire FSC, the full-chain nitrogen use efficiency ($NUE_{fc}$) drops to a mere 8% globally, with significant regional heterogeneities driven by agricultural NUE, FLW rates, dietary patterns and trade patterns. Notably, nitrogen losses embedded within the FSC are nearly four times higher than those occurring at the waste management stage, suggesting that improving end-of-pipe treatments alone offers limited mitigation potential (~6.3%). In contrast, an integrated strategy—comprising halving FLW, maximizing resource recovery, adopting plant-based diets, and optimizing trade distributions—could reduce FSC $N_r$ emissions by 26.0 Tg N (~24.8%) and nearly double the $NUE_{fc}$ to 14.7%. These findings highlight the critical need for holistic FSC interventions to safeguard global nitrogen and nutrient sustainability.

# The potential of organic waste recycling to replace mineral fertilizers in EU Member States

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**ABSTRACT**

Nitrogen (N), phosphorus (P) and potassium (K) inputs to soil by mineral fertilizers and organic sources (manure, sewage sludge and biowaste) differs among EU member states, ranging from inadequate inputs to deplete the soils to inefficient applications leading to nutrient losses [1]. Besides their supply N, P and K, organic resources also supply carbon and other major nutrients thereby improving soil fertility [2]. European policies thus promote nutrient recycling to decrease the dependency on imported mineral fertilizers produced outside Europe [3]. In addition, the mineral fertilizer supply can be reduced by balancing the nutrient supply to the crop nutrient demand.

Yet the potential of organic waste recycling to replace mineral fertilizers across Europe remains insufficiently quantified. Using country-level statistics on livestock and crop production, human population and biowaste generation, we estimated (i) currently (2020-2022) applied and the potentially recoverable nutrients under existing and improved nutrient recovery technologies in 27+3 member states in Europe, and (ii) the potential of organic waste recycling to replace mineral fertilizers based on crop demand assuming balanced fertilization.

Results show that potential nutrients in : (i) manure are 5525 ktons N, 1375 ktons P and 4737 ktons K, of which 72%, 75% and 70% is currently applied in arable land, respectively (the rest is applied in grassland), (ii) sewage sludge are 2698 ktons N, 523 ktons P and 572 ktons K, of which 5%, 18% and 3% is currently used in agriculture, respectively and (ii) biowaste are 795 ktons N, 159 ktons P and 477 ktons K, of which 51%, 32% and 46% is currently used in agriculture, respectively.

Assuming balanced N, P and K input based on crop demand, while maintaining the current organic nutrient supply already reduced current fertilizer use by 20%, 11% and 14% for N, P and K, respectively. When in the future all new and best treatment nutrient recovery technologies are applied, and all organic nutrients are recycled, then the fertilizer use can be reduced by 49%, 61% and 34% for N, P and K fertilizer, respectively compared to the current use.

Our findings highlight the substantial potential of organic nutrient recycling to reduce mineral fertilizer dependency in Europe, supporting policy development for nutrient circularity while safeguarding soil quality and environmental health.

**Acknowledgments**

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# Organic waste–derived soil amendments for climate-smart soil fertility management

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## ABSTRACT

Recycling organic waste into agricultural soils is a key strategy for circular nutrient management, improved soil fertility, and climate resilience. However, agronomic and environmental outcomes depend strongly on waste processing pathways, soil context, and potential greenhouse gas (GHG) trade-offs. This presentation synthesizes incubation, greenhouse, and field studies to evaluate how organic waste-derived soil amendments regulate nutrient availability, soil biological processes, and nitrous oxide ($N_2O$) emissions across contrasting soils and environmental conditions.

Incubation experiments show that thermochemically processed organic wastes substantially reduce $N_2O$ emissions compared with direct waste application, with effectiveness depending on soil texture and processing conditions, underscoring the need of pre-application screening. Field studies indicate that processed waste-derived amendments can lower $N_2O$ emissions relative to untreated organic waste without compromising crop yield, although whole-season climate metrics may not diverge in short-term assessments. From a soil fertility perspective, untreated organic waste resulted in the highest phosphorus uptake and use efficiency in a greenhouse study, while microbial indicators - particularly fungal and arbuscular mycorrhizal fungi markers - emerged as key drivers of nutrient acquisition. In addition, mineral-rich waste-derived amendments demonstrated potential to enhance crop performance under drought stress, linking organic waste recycling with climate-resilient agroecosystem management.

Overall, effective use of organic waste-derived amendments requires integrating waste processing strategies with soil-specific evaluation of nutrient cycling, biological mediation, and GHG risks to maximize soil fertility benefits while minimizing unintended environmental impacts.

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# The effects of different crop straw retention modes and nitrogen fertilizer rates on nitrogen runoff loss, crop yield and soil fertility in rice-wheat cropping systems

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**ABSTRACT**

The Crop straw retention has been established as an effective conservation tillage practice for decreasing nitrogen (N) runoff losses and increasing crop production. However, the impacts on N runoff losses from annual rice-wheat rotation are not well understood, which has prevented identification of optimal straw retention practice. Herein, N dynamics and losses in the runoff, crop yields, and soil properties were assessed for two years in a rice-wheat system after implementing straw return for five consecutive years. The field experiment included 7 treatments—N2, WN2, RN2: recommended N application with no straw, wheat straw, and rice straw retained, respectively; and SN0, SN1, SN2, and SN3: both wheat and rice straw return with zero, reduced, recommended, and custom N addition (0, 180, 240, and 300 kgN/ha for rice), respectively. The results showed that total N loss (TN, $P < 0.001$) and mean annual crop yield (rice and wheat, $P < 0.01$) significantly increased as the N fertilizer rate increased. With respect to crop straw retention modes, the cumulative TN loss and mean annual crop yield trends were: N2 > RN2 >WN2 >SN2 ($P < 0.05$) and SN2≥RN2 >WN2≈N2 ($P < 0.05$), respectively. During a one-year rice-wheat rotation cycle, the treatments with simultaneous incorporation of crop residue and N fertilizer reduced N runoff loss by 2.7–20.9% ($P < 0.05$) and increased crop yield by 8.7–16.9% ($P < 0.05$), of which the SN2 treatment was found to be the most effective. The straw-induced reducing effect occurred only during the base and tiller fertilization stages of the rice growing period, which was primarily regulated by soil inorganic nitrogen (SIN), soil organic carbon (SOC), and pH during the rice tiller stage. Structural equation modelling revealed that SIN ($r = 0.53$, $P = 0.007$) had the most direct positive effect on N runoff loss, but the effect was statistically compromised by the overall negative effects of SOC ( $r = -0.33$, $P = 0.034$), pH ($r = -0.15$, $P > 0.05$), and bacterial community composition ($r = -0.10$, $P = 0.041$), and to a less extent by α-diversity ($r = -0.04$, $P > 0.05$). The SOC, TN and available-K content in the RN2 and SN2 treatments were respectively 20.7–24.7% and 16.1–15.7% and 33.3–49.4% higher than those in the N2 treatment ($P < 0.05$). And both SOC and TN also showed an increasing trend as the N fertilizer rate increases. Our findings indicate that straw return decreases N runoff loss by mediating factors in soil and standing water. In order to reduce N runoff loss without jeopardizing crop yield, the practice of double seasons straw retention with recommended N application (SN2) is suggested in the rice-wheat rotation cropping system in southern China.

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# Repurposing Lake Sediments as a Sustainable Phosphorus Source for Spring Barley: A Case Study in Denmark

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**ABSTRACT**

Phosphorus (P) scarcity in agriculture and persistent eutrophication of freshwater ecosystems are two interconnected challenges. Lake sediment removal is often required to restore eutrophic lakes, as internal P loading from sediments can delay recovery even after external inputs are reduced. Repurposing dredged lake sediment for agricultural use offers a dual benefit: supporting lake restoration while providing an alternative P source for crop production. In recent years, the use of lake sediments as a soil amendment has increased, driven by sustainability goals and restoration incentives. However, its effectiveness as a fertilizer remains uncertain due to low P solubility and the limited number of field-based studies evaluating its agronomic performance.

Preliminary analyses indicate that a large portion of sediment P is bound to iron (Fe), limiting plant availability. Phosphorus-solubilizing microorganisms (PSMs) have therefore been proposed as a strategy to enhance P availability through the release of organic acids and enzymes that mobilize Fe-bound P. Beyond increasing plant-available P, PSMs may also provide additional benefits, such as promoting root growth, hormone-mediated stimulation, and improved soil structure, potentially enhancing the agronomic value of lake sediment.

This study evaluates the agronomic potential of lake sediment, alone and in combination with PSMs, using spring barley (*Hordeum vulgare* L.) under Danish field conditions as part of a three-year field experiment. Here, we present results from the first growing season. The experiment compares two P application strategies: (i) an annual application of 30 kg P $ha^{-1}$ on a total P basis, and (ii) a single application of 90 kg P $ha^{-1}$ followed by no additional P input for three years, both consistent with regulatory limits. Treatments include lake sediment, triple superphosphate (TSP), and control plots, each applied with or without PSM-coated seeds.

The objectives of the first-year assessment are to (i) evaluate the capacity of lake sediment, with and without PSMs, to function as an effective P fertilizer, (ii) assess the potential role of microorganisms in supporting crop growth and yield, and (iii) compare crop yield responses under different P dosing strategies. These initial results provide insight into the short-term agronomic performance of lake sediment-based fertilizers and inform expectations for subsequent years of the study.

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# Precision Nitrogen Management in Rice: Appraising Smartphone-Based Fertilizer Apps and Evaluating the Efficacy of Selected Nitrogen Management Strategies

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**ABSTRACT**

Nitrogen (N) management remains a critical challenge in rice-based systems, especially across South Asia, where fertilizer use is the highest, yet nitrogen use efficiency (NUE) remains persistently low. This study integrates a comprehensive review of 60 fertilizer management mobile applications (30 from South Asia and 30 beyond South Asia) with a field experiment evaluating app-guided and crop-responsive N strategies in two consecutive seasons of Boro rice cultivation. App profiling revealed the dominance of static calculators and generic advisories, with limited use of real-time diagnostics or crop-stage-specific logic. In contrast, field results showed that dynamic leaf-based tools Leaf Color Chart and SPAD chlorophyll meter achieved comparable yields to conventional and app-based methods, while significantly improving agronomic and recovery efficiencies of N. These tools enable precise, demand-driven N applications and reduce input use without compromising productivity. The findings underscore the crucial need to digitize physiologically aligned decision tools into mobile platforms, enabling real-time, field-specific N recommendations for smallholders. Such innovations can transform N management by enhancing NUE, reducing N losses, and improving environmental sustainability. This study calls for the development of next-generation, image-enabled, crop-stage-responsive N advisory apps tailored to smallholder realities. Policymakers should prioritize the development and dissemination of sensor-integrated fertilizer advisory apps to boost NUE, reduce emissions, and promote sustainable intensification of rice cultivation systems, particularly in high-input, low-efficiency regions like South Asia.

**Keywords:** Mobile app, Leaf color chart, Nitrogen use efficiency, Soil test

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# Effects of Annual Co-ordinated Phosphorus Fertilization under Wheat/Maize Rotation on Crop Phosphorus Uptake and Soil Phosphorus Content

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**ABSTRACT**

【Objective】 The overall phosphorus balance in Chinese farmland shows a trend of surplus, which is continuously intensifying. This study aims to investigate the effects of different crop rotation phosphorus fertilizer application ratios, reduction ratios, and reduction methods on phosphorus fertilizer use efficiency and soil quality.【Method】From October 2015 to September 2018, a year-round phosphorus fertilizer optimization experiment was conducted under a wheat–corn rotation system on two selected sites in Dezhou, Shandong Province: one high-phosphorus and one low-phosphorus field. The experiment was designed as a randomized block trial, with five treatments and three replicates. The treatments included: no phosphorus fertilizer throughout the year (P0), two-thirds of the annual phosphorus fertilizer applied during the wheat season and one-third during the corn season (CK), half of the annual phosphorus fertilizer (P0.5), phosphorus fertilizer applied every other year (P biennial), and phosphorus fertilizer applied only during the wheat season (P1). During each wheat and corn harvest season, plant and soil samples were collected to analyze crop phosphorus content, phosphorus fertilizer uptake and utilization, and soil available phosphorus content. Soil available phosphorus content was measured annually at depths of 0–20 cm, 20–40 cm, and 40–60 cm to analyze phosphorus variations across different treatments, soil depths, and rotation years.【Conclusion】 The experimental results indicate: (1) For fields with initially high soil phosphorus content, reduced phosphorus application can meet the phosphorus nutrient requirements of the aboveground parts of crops. A single concentrated fertilization during the wheat season can enhance the annual grain phosphorus uptake in high-phosphorus areas; (2) Compared with conventional phosphorus application, reducing phosphorus by half in high-phosphorus areas can increase phosphorus fertilizer recovery efficiency by 48.21% and phosphorus fertilizer partial productivity by 54.05 kg/kg. Under alternate-year phosphorus application, phosphorus recovery efficiency can be increased by 45.64%, phosphorus fertilizer partial productivity by 41.31 kg/kg, and agronomic efficiency by 1.68 kg/kg. Concentrated phosphorus application during the wheat season can increase the annual phosphorus fertilizer yield contribution rate by 6.13% and improve agronomic efficiency by 3.17 kg/kg; (3) In low-phosphorus areas, reducing phosphorus by half can increase phosphate fertilizer utilization rate by 34.32% and phosphorus fertilizer partial productivity by 35.10 kg/kg. Alternate-year fertilizer application can improve phosphorus recovery efficiency by 30.79% and phosphorus fertilizer partial productivity by 32.18 kg/kg. Concentrated phosphorus application during the wheat season can raise the annual phosphorus fertilizer yield contribution rate by 1.03%; (4) From the perspective of available phosphorus supply in the 0–20 cm plow layer, reducing phosphorus by half, alternate-year application, and concentrated wheat season application in high-phosphorus areas can fully meet nutrient requirements for two rotation cycles. However, a decrease in yield may occur from the third rotation cycle and subsequent maize seasons; (5) In low-phosphorus areas, alternate-year phosphorus application has effects on available phosphorus in the plow layer that are generally consistent with conventional phosphorus application, whereas reducing phosphorus by half or concentrated wheat season application may lead to insufficient soil phosphorus supply during some maize seasons in the rotation cycles.

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# Organic Fertilizer Substitution Boosts Maize Yield in Upland Acidic Red Soils by Enhancing Soil Quality and Nutrient Availability: Insights from a 7-Year Study

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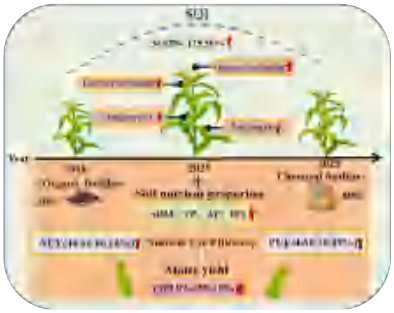
**ABSTRACT**

The substitution of organic fertilizers for chemical fertilizers has become a pivotal strategy for achieving a balanced nutrient supply and ensuring high, stable yields in maize and other crops. Although this approach has shown marked success in many regions, its long-term effects on soil quality and the mechanisms underlying its enhancement of crop growth remain unclear. Accordingly, a seven-year field experiment (2017-2023) was conducted in a typical subtropical red soil region of China to evaluate the long-term effects of organic fertilizer substitution on soil quality, maize yield, and nutrient use efficiency (NUE and PUE). The experiment applied five treatments: no fertilization (CK), chemical fertilizer (CF), and organic fertilizer substituting 20%, 40%, and 100% of chemical N (COF20%, COF40%, COF100%). The results showed that all fertilized treatments significantly improved the soil quality index (SQI) and maize yield compared with CK. Among these, COF20% and COF40% achieved the highest SQI and yield, increasing SQI by 54.52-115.56% and yield by 329.97-599.15%. From 2022 to 2023, soil properties and crop indices remained relatively stable ($p > 0.05$). Structural equation modeling indicated that improvements in soil organic matter (SOM), total phosphorus (TP), available phosphorus (AP), and hydrolyzable nitrogen (HN) were the main drivers of SQI enhancement and yield increase. These factors also promoted nitrogen and phosphorus utilization efficiency. Overall, partial substitution with organic fertilizer, especially COF20%, robustly enhanced soil fertility, nutrient use efficiency, and maize yield in a cost-effective manner. This strategy provides a viable pathway for fostering sustainable and resilient agricultural systems in upland regions.

**Keywords:** Soil quality; Nitrogen and phosphorus utilization efficiency; Maize yield; Upland acidic red soil; Rain-fed agricultural region.

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# Evolution characteristics of soil phosphorus and its availability under long-term fertilization in black soil region, China

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**ABSTRACT**

Based on the long-term fertilizer experiment in Harbin, Heilongjiang Province, China(1979~2021), to study the evolution characteristics and availability changes of phosphorus (P). Contents of soil total phosphorus (TP) and Olsen phosphorus (Olsen-P) and their linear regressions were analyzed and calculated. The results showed that contents of TP and Olsen-P under treatments of phosphorus fertilizers (P, NP, PK, and NPK) increased significantly after 42 years of fertilization, with an average increase of 0.73g/kg and 77.6 mg/kg, respectively, compared to the initial content. While, contents of TP and Olsen-P decreased with the extension of fertilization years under treatments of no P fertilizer (CK, N, K, and NK)(with reductions of 18.3% and 53.6%, respectively). P availability coefficient (PAC) showed yearly declining trends under treatments of no P fertilizer, but had increasing trends with P fertilizer. The PAC of P fertilizer treatments were higher than that under treatments of no fertilizer and no P fertilizer. Soil Olsen-P increment after P application was positively correlated with the accumulated of P. For every P of 100 kg/ha surplus in the soil,Olsen-P increased by 2.34 mg/kg, 2.96 mg/kg, 1.82 mg/kg and 2.89 mg/kg in treatments of P, NP, PK and NPK. When the soil P balance was in deficient, the Olsen-P content under treatments of CK, N, K and NK would be decreased by 1.17 mg/kg, 0.87 mg/kg, 0.83 mg/kg and 1.16 mg/kg for every deficiency of P 100 kg/ha, respectively. In general, the application of P fertilizer could increase contents of soil TP and Olsen-P totally, with PAC being overall higher than treatments of no fertilizer or P fertilizer. Increment of Olsen-P varied closely with the change of soil P balance. The rational application of P fertilizer is of great significance for maintaining soil P surplus and increasing its availability in black soil regions.

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# Nutrient status and fertility constraints of highly weathered oil palm-growing soils in Thailand

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**ABSTRACT**

Oil palm (*Elaeis guineensis* Jacq.) is a major economic crop, with Indonesia, Malaysia, and Thailand producing 86% of the global supply (FAO, 2023). This study evaluated the nutrient status and main fertility constraints of soils used for mature oil palm plantations (5–17 years old) in Surat Thani province, southern Thailand. Composite surface soils (0–20 cm) from representative Typic Kandiudults (OP1 and OP2), Typic Paleudults (OP3 and OP4), and a Sulfic Endoaquepts (OP5) were analyzed for texture, pH (1:1 $H_2O$), electrical conductivity (ECe), organic matter (OM), cation-exchange capacity (CEC), available P, and extractable K, Ca, Mg, and B using standard methods (Soil Survey Staff, 2014; FAO, 2024).

Soil properties varied markedly across sites. Texture ranged from sandy loam in OP1–OP4 to silty clay in OP5, showing contrasting nutrient-retention capacities. All soils were ultra-acid to very strongly acidic (pH 3.28–4.58), which decreases nutrient availability and promote base-cation leaching. ECe values ranged from 0.43 to 2.31 dS $m^{-1}$, indicating non-saline conditions. OM was low to moderate (7.79–17.8 g $kg^{-1}$) in OP1–OP4 but higher in OP5 (30.8 g $kg^{-1}$), consistent with CEC results, which ranged from very low to moderately low (2.50–7.50 $cmol_c$ $kg^{-1}$) in OP1–OP4 and were substantially higher in OP5 (22.5 $cmol_c$ $kg^{-1}$), reflecting differences in OM content and clay mineralogy. Available P varied widely (16.49–329 mg $kg^{-1}$), with the highest values in OP5, likely influenced by historical fertilizer use and enhanced P retention. Extractable K ranged from 60.8 to 1,096 mg $kg^{-1}$, while Ca (130–701 mg $kg^{-1}$) and Mg (29.3–237 mg $kg^{-1}$) were mostly low in OP1–OP4, indicating substantial leaching losses and base-cation depletion. Extractable B in OP1–OP4 (6.25–16.7 mg $kg^{-1}$) was uniformly high, consistent with soils receiving B fertilization, whereas OP5 showed an exceptionally high concentration (78.2 mg $kg^{-1}$), indicating substantial B accumulation due to heavy or repeated applications. Overall, these findings highlight major fertility constraints in oil-palm-growing soils and emphasize the need for targeted nutrient-management strategies to sustain productivity.

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# Fertilizer Use and Nutrient Management in Indian Agriculture

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**ABSTRACT**

Fertilizer is the important component of agricultural development in the world and India is no exception. On all counts, accomplishment on the production of food grain front has paralleled the consumption of fertilizers since the 1960s in India. Government implemented policies from time to time to give impetus to fertilizer use.

Deterioration of soil health is considered as one of the main reasons of declining nutrient use efficiency *vis-à-vis* stagnation of agricultural productivity in tropical regions without exception of India. Post Green Revolution, sharp increase in the use of high analysis fertilizers to meet the nutrient demand of HYVs and decrease in use of organic manure due to shifting of animal-based farming to mechanized agriculture resulted in multi-nutrient deficiencies and deterioration of soil physical and biological health over the years. Organic carbon in soil is on decline. The fertilizer response ratio (kg grain per kg nutrient) decreased from 13.5 in 1960-69 to 5.0 in 2010-17) in irrigated areas of the country.

Systematic analysis of data from long-term fertilizer experiments showed that: complete recommended dose of fertilizers (RDF or 100% NPK) applied to soils initially low in soil organic carbon (SOC) (< 7 g $kg^{-1}$ soil) sustained productivity and significantly improved SOC content, indicating thereby protection to soil health. Contrarily, RDF failed to sustain productivity and SOC of soils initially high in its content (>7 g SOC $kg^{-1}$ soil). Integrated use of organic manures (equivalent to 25-30% of RDF) plus fertilizers (70% to 75% of RDF) raised productivity and level of SOC, irrespective of initial SOC content. Use of vermicompost, FYM and bio-fertilizers improves endophytic bacterial diversity compared to mineral fertilizers. Further, results of long-term experiments conducted from 1972 to 2002 at four locations of 4 states of India demonstrated that integrated use of recommended dose of 100% NPK with 5 MT FYM $ha^{-1}$ is necessary to enhance populations of bacteria, fungi and actinomycetes as the results were observed to be better than control, 100% N, 100% NP and 100% NPK. Balanced NPK was found to be better compared to N or NP.

Use efficiency of applied fertilizers is low. Promotion of better nutrient management strategy among the farmers is vital to improve soil health, farm productivity and to minimize the environmental footprints on sustainable basis. Conservation agriculture with its three basic principles of minimum soil disturbance, permanent soil cover, and crop rotation could be a viable option for meeting the targets of SDGs (Chaudhari et al., 2021).

To mitigate the adverse effect of climate change, Government of India and Indian Council of Agricultural Research (ICAR) has initiated several programs/schemes/research projects. Leveraging digital tools is poised to play a pivotal role in adoption of 4R Stewardship Principle of nutrient management involving application of Right Source, at the Right Rate, at the Right Time, and in the Right Place**.** The soil health & fertility scheme of the Government of India has emerged as a transformative intervention in Indian agriculture, laying the foundation for sustainable soil and nutrient management.

There is no much improvement in NUE in the country. All stakeholders namely the Government, research institutions and fertiliser industry are concerned for the ways and means to improve the NUE. Efforts like use of 100% neem coated urea; promotion of 100% water soluble fertilizers, micronutrients, bio-stimulants, liquid and customized fertilisers; impetus to new formulations; arena of Nano-based fertilizers undergoing rapid expansion through development of Nano urea and Nano DAP; promotion of bio-fertilizers, etc. would go a long way to improve NUE considerably. The country is on forefront to use N-(n-butyl) thiophosphoric triamide – a urease inhibitor, to improve use efficiency of applied urea.

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# The role of fertilizers for feeding the world

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**ABSTRACT**

Over the last century, inorganic fertilizers (also sometimes referred to as mineral or synthetic fertilizers) have played a key role in the food security of billions of people. Fertilizers supplied nutrients to crops on soils with insufficient natural supply and/or where organic fertilizers were not or too little available to sustain crop production. As such, inorganic fertilizers have closed the balance for the nutrients lost from fields as harvested biomass, leaching and emissions. Farmers across the world have therefore relied on fertilizers to increase crop yields over time yet the size of this contribution is uncertain. Quantification of fertilizers' contribution to food production will allow more informed nutrient management as well as identification of food system vulnerabilities to disruptions in the supply of fertilizer.

In this study, we used two approaches of estimating fertilizers contribution to food production worldwide, namely (1) a nutrient supply and (2) an agronomic nutrient use efficiency approach. These approaches were applied to elemental nitrogen (N), phosphorus (P) and potassium (K) in inorganic fertilizer applied to cropland worldwide. The Nutrient Supply approach assessed fertilizers contribution to food based on the share of total nutrient inputs provided as inorganic fertilizer using data from the FAO Cropland Nutrient Balance. The Agronomic efficiency approach used long-term (>5 year duration) experiments to derive the agronomic nutrient use efficiencies (AE; i.e. change in yield from the addition of fertilizer divided by the change in nutrients applied to the fertilized treatment), while accounting for soil legacy effects. The AE values were applied to surveyed data of fertilizer use by crop and country to estimate the additional quantity of crop production resulting from fertilizer. Estimates of crop production from fertilizer were divided by the total quantity of crop production per region to estimate fertilizers' contribution to food.

Using the Nutrient Supply approach we estimated that, on average over the 1961-2022 period, N, P and K fertilizers accounted for 50%, 70% and 40% of the total cropland N, P and K inputs, respectively. Inorganic fertilizer as a share of total inputs increased steadily since 1961, but its share varied widely by countries and regions. The exception to this was for N whose change in share of total inputs plateaued in the last ~ 30 years. Estimates of fertilizers' contribution to food production using the agronomic efficiency approach were generally lower than those estimated using the nutrient supply approach, with the greatest contributions estimated for Asia and the lowest contributions for Africa. Results of our two methods of estimating fertilizers' contribution to food production should be accounted for when policy-makers consider making changes to fertilizer policies.

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# Emerging soil nutrient limitations for global crop production

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**ABSTRACT**

Achieving high crop yields requires an adequate supply of essential mineral nutrients, yet global attention and research investment have remained disproportionately focused on nitrogen and phosphorus compared to other macronutrients such as potassium (K) and sulfur (S). Intensification of farming systems, characterized by higher crop yields and depletion of native soil reserves, exacerbate current K and S limitations to crop production. In this study, we assessed the degree of K limitation in major agroecosystems worldwide and investigated the underlying drivers. Our approach integrates global datasets collected after 2000, including soil K measurements (n = 3.6 M), on-farm K balances (n = 111,000), and yield responses to K fertilizer in short -term experiments (n = 66,300), complemented by crop modeling and statistical analysis. Cropping systems were classified into four groups based on K balance status and yield responsiveness to fertilizer. The first group includes systems where K addition is not common, yet crop responsiveness and negative K balances (-39 kg K $ha^{-1}$ $y^{-1}$) are increasing (e.g., South American Pampas and western US Corn Belt). The second includes systems where yield response to K fertilizer is widespread, but K balances remain negative (-27 kg K $ha^{-1}$ $y^{-1}$) due to insufficient fertilization, high cropping intensity, and straw removal (e.g., south and southeast Asia). The third represents systems where soil K supply is insufficient for crop demand, but current K inputs appear sufficient or excessive relative to present yields (e.g., Brazilian Cerrado and China). The last group includes low-input, low-yield regions where K limitation was inconsistent, likely due to limitation by other factors (e.g., Sub-Saharan Africa). The economic analysis shows that K fertilizer application is profitable (285 US$ $ha^{-1}$ $y^{-1}$) in the second and third group (e.g., south and southeast Asia and China). Our study also shows that global K fertilizer requirement will increase from 14 to 24 MMT for a scenario of crop intensification where current crop yields reach 80% of yield potential. Because crop residue removal greatly affects K outputs, the K input needed to sustain attainable yields would increase to 33 MMT if residue removal increases from the current 41% to 75% in the future. Building on the same data-driven analytical framework, we are conducting a parallel global assessment of sulfur limitation. Preliminary S results indicate increasing risk of S deficiency in areas with reduced atmospheric deposition, intensified crop removal, and limited S fertilization. Overall, our findings highlight that soil K and S supply is seldom adequate to sustain current yields, and that closing global yield gaps will require improved K and S management strategies tailored to regional production systems.

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# Soil fertility and nutrient status of long-term durian orchards under organic–chemical management in Chanthaburi, Thailand

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**ABSTRACT**

Durian (*Durio zibethinus* Murr.) is one of Thailand's most economically important tropical fruit crops, yet long-term continuous cultivation has raised concerns about soil nutrient imbalance and phosphorus (P) accumulation. This study aimed (1) to assess the soil nutrient status of durian orchards cultivated for more than 25 years under an organic–chemical mixed management system, and (2) to quantify P residues resulting from long-term fertilization. Soil samples were collected from farmer orchards in Thung Bencha Subdistrict, Tha Mai District, Chanthaburi Province, at two depths (0–20 and 20–40 cm) beneath four cultivars (Chanee, Puangmanee, Monthong, and Kanyao). Samples were analyzed for texture, pH, electrical conductivity ($EC_{1:5}$), organic matter (OM), Bray II–extractable P, $NH_4OAc$-extractable K, Ca, and Mg, and DTPA-extractable Fe, Cu, Mn, and Zn (Soil Survey Staff, 2014). Total P (perchloric acid digestion), organic P (ignition method), and inorganic P were determined following Kuo (1996).

The soils were predominantly sandy clay loam and extremely acidic (pH 3.93–4.32), conditions that intensify nutrient limitations and promote cation leaching. $EC_{1:5}$ values were low (0.03–0.07 dS $m^{-1}$), while OM contents were relatively high (29.3–39.8 g $kg^{-1}$). Extractable P levels were extremely high (93.2–210 mg $kg^{-1}$), indicating substantial long-term P accumulation. In contrast, extractable K, Ca, and Mg were low (13.5–33.2 mg $kg^{-1}$; 72.1–183 mg $kg^{-1}$; 13.1–22.9 mg $kg^{-1}$), reflecting severe depletion of base cations under prolonged acidic conditions. Micronutrient concentrations were within moderate to high ranges (Fe: 59.1–152 mg $kg^{-1}$; Cu: 0.50–2.56 mg $kg^{-1}$; Mn: 1.11–2.64 mg $kg^{-1}$; Zn: 0.48–1.99 mg $kg^{-1}$). Most nutrients were significantly more concentrated in the topsoil than in the subsoil ($P < 0.05$), indicating fertilizer-driven nutrient accumulation in the upper horizon. Total soil P was also remarkably high (427–767 mg $kg^{-1}$), dominated by inorganic P (351–649 mg $kg^{-1}$; 77–85%), whereas organic P accounted for only 18–23%, confirming persistent P loading in the soil profile. Overall, these findings reveal a pronounced nutrient imbalance characterized by excessive P accumulation and critical deficiencies of K, Ca, and Mg under long-term organic–chemical durian cultivation. The results highlight the urgent need to reduce P inputs and replenish depleted base cations to sustain soil fertility and maintain long-term orchard productivity in eastern Thailand.

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# Soil organic C composition and microbial community regulate soil enzymatic stoichiometry in Camellia oleifera land with cover crops

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**ABSTRACT**

Cover cropping helps improve soil conditions in *Camellia oleifera* —an important edible oil tree species predominantly grown in hilly red soil regions of southern China. Soil extracellular enzymes play vital roles in nutrient transformations. However, how cover crops influence soil enzymatic stoichiometry and its underlying regulatory mechanisms in *Camellia oleifera* plantations remains unclear. In this study, we examined soil extracellular enzymes, organic carbon composition, and microbial communities across two seasons in a long-term field experiment involving different cover crops: natural grass cover (control), Coreopsis tinctoria (CT), Festuca arundinacea (FA), Trifolium repens (TR), and Cosmos bipinnatus (CB). The results showed that, compared with the control, artificial cover crops significantly improved soil physicochemical properties. During the growth period of *Camellia oleifera* (June), TR and CB significantly increased the contents of ammonium nitrogen, nitrate nitrogen, available phosphorus, soil organic carbon, and particulate and mineral-associated organic carbon. From the growth period to the maturation period (October), soil extracellular enzyme activities generally increased, and microbial nutrient limitation shifted from phosphorus to nitrogen limitation. The decrease in vector length indicated a relief of carbon limitation. Fungi had a more significant impact than bacteria on organic carbon components and enzyme activities, with TR and CB exerting the most pronounced effects on soil organic carbon accumulation and fertility improvement by regulating fungal communities and enzyme activities. This study highlights the role of labile soil organic carbon and fungal communities in regulating enzymatic stoichiometry in *Camellia oleifera* plantations.

**Keywords:** *Camellia oleifera*; Grass-planting patterns; Enzyme activity; Nutrient limitation; Soil microorganism

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# Effects of Foliar Potassium Nitrate on Chlorophyll and Leaf Macronutrients in Sugarcane

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## ABSTRACT

Sugarcane (*Saccharum officinarum* L.) is an economically important crop worldwide, yet increasing yield remains challenging, particularly for ratoon crops. This study investigated the effects of foliar potassium nitrate ($KNO_3$) supplementation on chlorophyll content and nitrogen (N), phosphorus (P), and potassium (K) concentrations in second-ratoon sugarcane (var. Khon Kaen 3). The experiment was conducted at the Department of Soil Science experimental field, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, using a 4 × 3 factorial arrangement in a randomized complete block design. Treatments consisted of four $KNO_3$ concentrations (0, 1.5, 2.5, and 3.5% w/v) and three spray volumes (667, 1333, and 2000 L $ha^{-1}$), with three replications. Soil-applied NPK fertilizers were applied according to recommended rates for ratoon cane (Department of Agriculture, 2021). Foliar $KNO_3$ was applied when the ratoon cane was 6 months old. Chlorophyll content was measured three weeks after application using a SPAD-502Plus meter, and index-leaf samples were collected for analysis of N, P, and K. Statistical analysis was performed using an F-test, followed by Duncan's Multiple Range Test at the 95% confidence level.

Foliar $KNO_3$ application significantly increased chlorophyll content and leaf N, P, and K concentrations. The highest chlorophyll content occurred with 2.5% $KNO_3$ at 667 L $ha^{-1}$ (SPAD = 45.5), which also produced the highest leaf N and K concentrations (13.5 and 19.79 g $kg^{-1}$, respectively). In contrast, the greatest P concentration (1.65 g $kg^{-1}$) was observed in the treatment receiving 2.5% $KNO_3$ at 2000 L $ha^{-1}$. Foliar $KNO_3$ application enhanced chlorophyll formation and improved leaf N and K nutritional status in second-ratoon sugarcane, likely because the nitrate supplied promoted chlorophyll synthesis and facilitated the mobility of N and K within plant tissues. The variation in P among spray volumes suggests that canopy coverage and solution deposition influence foliar nutrient absorption. Comparison with published sufficiency ranges (McCray & Mylavarapu, 2020) showed that leaf K exceeded the "sufficient plus" category (>16 g $kg^{-1}$), whereas leaf N and P remained below their sufficiency thresholds (N: 20–23 g $kg^{-1}$; P: 2.2–2.6 g $kg^{-1}$). These findings highlight the potential of foliar $KNO_3$ as a supplementary practice in ratoon cane management, while emphasizing the need for improved soil- or foliar-based N and P nutrition strategies.

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# The Effect of Nutrient Management on Yield and Fruit Quality of Nam Hom Coconut in Thailand

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**ABSTRACT**

The Nam Hom coconut (*Cocos nucifera* L.), an aromatic coconut, is frequently harvested every 24-27 days, which can lead to soil nutrient depletion and potentially affect yield and fruit quality over time. This study investigated the effects of different nutrient management on the yield and fruit quality of Nam Hom coconut. The experiment was conducted at a coconut plantation in Ratchaburi Province, Thailand. The soil is derived from alluvial sediments and classified as *Vertic (Aeric) Endoaquepts*. There were four N-P-K fertilizer regimes (T1; 0.8-0-0.9, T2; 0.6-0.2-1.2, T3; 0.6-0.2-0.8, and T4; 0.8-0.2-0.8 kg N-$P_2O_5$-$K_2O$ tree$^{-1}$ year$^{-1}$) were applied based on crop nutrient removal. The fertilizer rate was divided into five equal applications every two to three months. Each treatment consisted of 28 trees, six of which were randomly selected for soil and leaves nutrient analyses, while yield was recorded from all trees and fruit quality from sampled fruits. No significant differences in soil nutrient concentrations were observed among treatments based on every two months monitoring throughout the experiment. However, all treatments showed a continuous increase in soil nutrient levels over the 12-month period. Treatment 3 showed the highest exchangeable K compared with the other treatments, although the difference was not statistically significant. In addition, available P also increased markedly compared with the initial soil condition. For nutrient concentration in leaves, there were not significantly different for nitrogen and phosphorus among treatments, whereas potassium showed significant difference, with Treatments 4 and 3 exhibiting the highest concentrations, respectively ($p<0.01$). The leaves nutrient levels tended to increase during the rainy season (October 2023) and decreased during the cool season (February 2024).

The cumulative yield of Nam Hom coconut increased all treatments, especially treatments 1 and 2 showing the highest yields. These two treatments had the greatest increase in fruit number. For fruit quality, treatment 3 showed the highest sweetness (7.53 °brix) and electrical conductivity of coconut water, with significant differences ($p < 0.05$). High potassium accumulation was also observed in coconut water across treatments. Correlation between nitrogen and potassium in leaves were significantly associated with coconut water sweetness, while flesh thickness was positively correlated only with potassium. These results suggest that N and K are key nutrients influencing fruit quality and yield of coconut productivity.

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# Cropland nutrient use efficiency: recent trends and targets for sustainable agriculture

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**ABSTRACT**

In cropland, the major inputs of nutrients are mineral fertilizers, manure, biological nitrogen (N) fixation, atmospheric deposition and seed. The primary nutrient output is in the form of the harvested main product. The difference between these inputs and outputs is the nutrient balance, whereas the ratio of outputs/inputs is an indicator of nutrient use efficiency. We present a global database of country-level balance and use efficiency estimates for N, phosphorus (P) and potassium (K) in cropland. The database, disseminated in FAOSTAT, provides a global References, synthesizing and continuously updating the state-of-the-art on this topic. The database covers 205 countries and territories, as well as regional and global aggregates, for the period 1961 to 2023.

Results highlight the wide range in nutrient use and use efficiencies across geographic regions, nutrients, and time. The greatest contributors to nutrient inputs in recent years were synthetic fertilizers, followed by biological N fixation for N, and manure applied to the soil for P and K. The global N surplus on cropland rose from 21 Mt in 1961 to 81 Mt in 1988, but has remained relatively unchanged at about 85 Mt in the past 15 years. Despite rising N inputs, the average global cropland N balance has remained fairly stable at about +50-55 kg $ha^{-1}$ $year^{-1}$ during the past 15 years, which is also reflected in an increase of N use efficiency, from a low of 43% in 1988 to 55% at present. This reflects yield growth, but also progress in adoption more N-efficient practices. However, regional and national trends vary widely, ranging from large N surpluses in Asia, particularly China and India, to long-term nutrient deficits of N, P and K in much of sub-Saharan Africa to. When nutrient removal with crop residue was included in the balance, K balances became negative in many regions, suggesting that K is likely to become a significant limitation to global crop yields.

Indicators such as nutrient balance (N, P, K) and N use efficiency are important for setting realistic, national targets for food security, soil health and environmental impact, and monitoring progress towards achieving them. We highlight several examples for that, discuss data uncertainties and provide priorities for further improvement.

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# Synergistic Effects of Mineral and Bio-organic Fertilizers Combined Application on Soil Multifunctionality and Yield and Quality of Coffee

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**ABSTRACT**

To investigate the synergistic effects of new mineral fertilizer (main components $K_2SO_4$-$MgSO_4$-$2CaSO_4$-$2H_2O$) and its combined application with bio-organic fertilizer on soil fertility and soil multifunctionality in coffee plantation and the yield and quality of coffee. A seven-year continuous field experiment was conducted in Yunnan, China. Five treatments included no fertilization (CK), two local conventional fertilization (SOP, MOP), mineral fertilizer application (POLY), and mineral fertilizer combined with bio-organic fertilizer (POF) application were set. The soil physical and chemical properties, soil nutrients, soil enzymes activity and coffee fresh fruit yield and quality were analyzed. The differences among treatments were examined using one-way analysis of variance (ANOVA), and the soil multifunctionality was studied with the Average Value Method. The results showed that, the combined application of mineral fertilizer and bio-organic fertilizer (POF) synergistically enhanced soil fertility and soil biological activity, thereby significantly improved soil multifunctionality in coffee plantation. Compared with the conventional fertilization SOP and MOP, POF increased soil fertility comprehensive index (IFI) by 33.3% and 36.1% respectively,the content of soil microbial biomass carbon (MBC) and nitrogen (MBN) increased by 41.46% and 55.01%, and by 15.28% and 16.58%, respectively, while significantly enhanced the activities of urease, sucrase, and β-glucosidase. Consequently, the soil multifunctionality index (SMF) increased 28.2% and 32.1%, respectively. The yield of fresh coffee fruit increased 17.8% and 28.3%, and the green coffee bean quality index (FQI) improved 29.24% and 35.59%. The comprehensive ranking of soil multifunctionality and coffee yield and coffee quality across all treatments consistently followed the order: POF > POLY > MOP > SOP > CK. Additionally, correlation analysis revealed that SMF was significantly positively correlated with both coffee yield and FQI ($P < 0.01$). The random forest model further indicated that soil organic carbon, extractable calcium, microbial biomass carbon, microbial biomass nitrogen, available potassium, urease and sucrase were the key indicators influencing soil multifunctionality in coffee plantations. In conclusion, the combined application of mineral fertilizer and bio-organic fertilizer can enhance soil fertility and soil multifunctionality of coffee plantation and improve yield and quality of coffee green bean. This provides an effective fertilization strategy for synergistic improving coffee quality and yield and sustainable production in coffee plantations.

**Keywords:** Coffee; Mineral fertilizer; Bio-organic fertilizer; Soil multifunctionality; Yield and quality

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# Calcium in Peanut Production: Towards Improved Nutrient Use Efficiency

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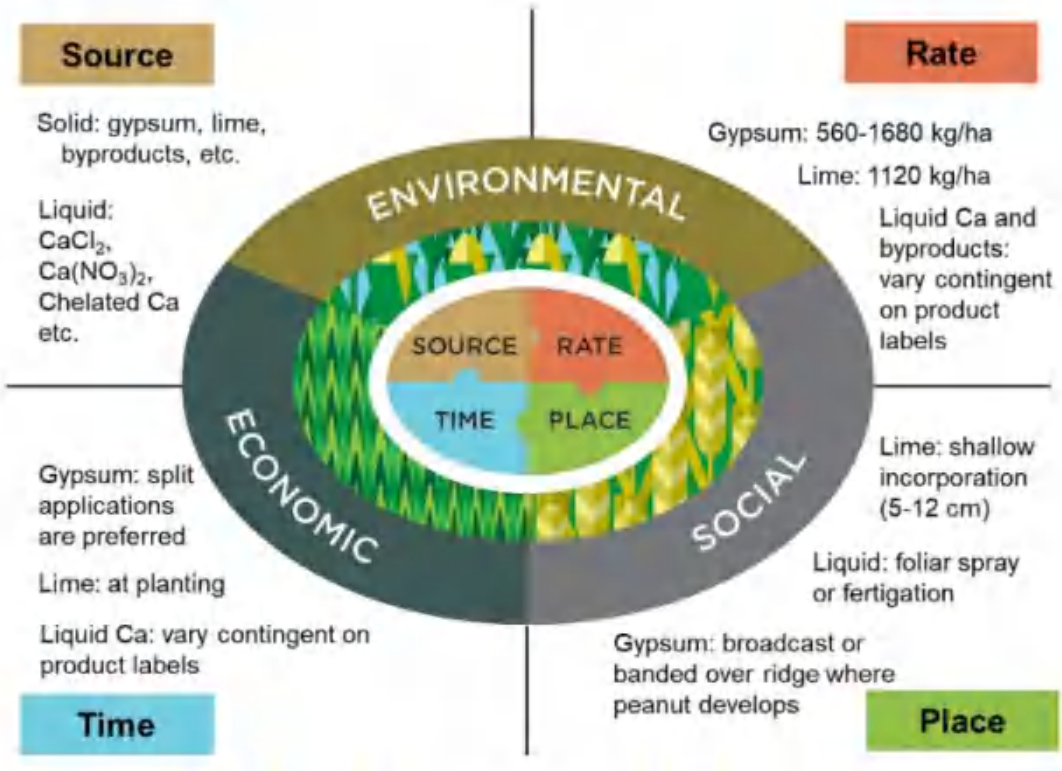
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**ABSTRACT**

Peanut (*Arachis Hypogea* L.) is a multifaceted crop with global importance. As an essential nutrient for higher plants, calcium (Ca) is particularly critical in peanut production. Insufficient Ca supply leads to low yield, substandard seed quality, and higher incidence of pathogen infection. However, soils suitable for peanut production are often low in Ca availability. It is thus important to ensure adequate Ca supply during peanut production. Improvement of crop productivity including nutrient use efficiency can be achieved through two main strategies: optimizing agronomic practice and breeding nutrient efficient crop cultivars. The improvement of Ca use efficiency in peanut through breeding effort is lagging far behand, it is more feasible to maintain and improve peanut productivity by optimizing nutrient management practices. In this work, molecular mechanisms of Ca-mediated peanut pod development are summarized, which offers new insights into breeding Ca-efficient peanut cultivars. In addition, enhancement of Ca use efficiency through nutrient management practices including Ca source, rate, timing, placement, and irrigation are thoroughly discussed. Research gaps and future endeavors regarding Ca use efficiency in peanut are also identified.




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# Organic Fertilizer Substitution Reshapes Carbon Component Distribution in Soil Aggregates Driving Niche Differentiation of Nitrogen Functional Microorganisms and Regulating Nitrogen Use Efficiency

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**ABSTRACT**

Long-term use of chemical fertilizers leads to soil texture and structure degradation, carbon-nitrogen imbalance, and reduced nitrogen use efficiency (NUE). Partial substitution of chemical fertilizers with organic fertilizers is a key strategy for improving soil health and nutrient cycling, but the microscale mechanisms by which different organic fertilizers regulate the distribution of carbon components in soil aggregates, thereby affecting the spatial distribution of nitrogen functional microorganisms and NUE, remain unclear. In this study, an 8-year field experiment was conducted with seven fertilization treatments, including chemical fertilizer alone and organic fertilizer substitution using pig manure (30%, 60%, and 100% of substitution ratio) or rapeseed cake (30% and 60% of substitution ratio). Aggregate composition and carbon fractions (particulate organic carbon, POC; mineral-associated organic carbon, MAOC; microbial biomass carbon, MBC), together with nitrogen-cycling microbial communities (abundances of *amoA*-AOA, *amoA*-AOB, *nirK*, *nirS*, *nosZI*, and *nosZII*), were quantified. Organic substitution improved aggregate stability and altered carbon allocation. The 60% rapeseed cake substitution ($COF_{60}$) had the highest proportion of macroaggregates (51.92%) and increased POC and MAOC contents, whereas pig manure substitution enhanced MBC accumulation. NUE was highest in clay fractions, with partial organic substitution (30-60%) increasing NUE by 13.6-27.4%. Nitrogen-cycling functional genes showed distinct spatial distributions: the *amoA* of AOA and AOB gene abundances were enriched in MAOC-rich clay fractions, whereas *nirK* and *nirS* gene abundances were concentrated in POC-rich macroaggregates. The $OF_{60}$ treatment had the highest *nirK* and *nirS* gene abundances ($8.07\times10^5$ and $9.07\times10^5$ copies·$g^{-1}$). Structural equation modeling revealed significant positive relationships between POC contents and the (*nirS*+*nirK*)/(*nosZI*+*nosZII*) ratio (0.58, $P<0.01$), and between MAOC contents and the AOA/AOB ratio (0.65, $P<0.01$). In turn, the (*nirS*+*nirK*)/(*nosZI*+n*osZII*) ratio exerted a negative effect on NUE ($P<0.001$), whereas the AOA/AOB ratio positively affected NUE (0.49, $P<0.05$). Overall, organic fertilizer substitution reshaped the spatial distribution of carbon components in soil aggregates, driving the differentiation of nitrogen functional microorganisms: POC promoted denitrifier enrichment, while MAOC enhanced ammonia-oxidizing populations, jointly forming a coupled “carbon-microbe-NUE” regulatory mechanism that links aggregate-scale carbon stabilization with nitrogen transformation efficiency and supports the design of optimized organic substitution strategies.

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# An organic nitrogen metabolite shapes soil–plant–microbe interactions and plant nitrogen acquisition

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## ABSTRACT

Sustainable agricultural systems increasingly rely on mineralization of large organic nitrogen (N) pools, with organic fertilizers such as compost, manures, and crop residues partially substituting for synthetic inorganic N inputs. However, plant organic N acquisition pathways remain poorly resolved. Although plants are now known to directly take up and assimilate organic N, most studies have focused on amino acids, overlooking the substantial diversity of organic N metabolites—including nucleobases, nucleosides, and amino sugars—that may serve as alternative N sources and modulate plant–microbe interactions governing N cycling and uptake.

Here, we first screened 26 low–molecular weight organic N-containing compounds commonly detected in soils as potential N sources for the model grass *Brachypodium distachyon* and identified the nucleobase uracil as a particularly promising compound that stimulated root growth. We then compared plant uptake from organic N (uracil) and inorganic N ($NH_4^+$, $NO_3^-$) using a short-term $^{15}N$-labeling experiment. Plants were cultivated for 5 weeks in unfertilized marginal soil amended with uracil, $KNO_3$, or $(NH_4)_2SO_4$. Subsequently, pots received solutions containing equal amounts of ammonium-N, nitrate-N, and uracil-N, with only one N form $^{15}N$-labeled ($NH_4$-$^{15}N$, $NO_3$-$^{15}N$, or uracil-$^{15}N$). Plants and soils were harvested 40 h after labeling to quantify $^{15}N$ in plant tissues and soils and to relate N uptake patterns to rhizosphere microbial communities characterized by 16S rRNA gene sequencing.

We observed enhanced plant N assimilation following shifts in N source, both from inorganic N to mixed inorganic–organic N and from organic N to mixed N. This may reflect transient decoupling between microbial demand and the newly supplied N form, leaving more available N for plant uptake. Uracil pretreatment increased soil microbial biomass C, indicative of stimulated microbial activity and potentially accelerated nutrient cycling. Uracil pretreatment also significantly altered rhizosphere bacterial community composition and diversity, notably increasing the relative abundance of *Nitrospirota*, which was positively correlated with shoot and root biomass and with soil $NH_4^+$ and $NO_3^-$ concentrations.

Collectively, our findings identify nucleobases as overlooked organic N sources capable of restructuring rhizosphere microbiomes and enhancing plant N acquisition, thereby advancing our understanding of how specific organic N compounds and their uptake pathways influence soil microbial processes and plant nutrition.

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# A meta-analysis and monte carlo simulation of nitrogen management strategies on balancing yield and environmental impact

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## ABSTRACT

Excessive nitrogen (N) losses from wet and warm sugarcane cropping systems pose severe environmental risks, yet mitigation strategies often carry uncertainties. While individual management practices have been widely studied, a comprehensive evaluation of their trade-offs remains limited. We compiled global sugarcane data and conducted meta-analysis to estimate the effects of management practices (inhibitors, straw retention, reduced N, carbon materials) on $NH_3$ volatilization, $N_2O$ emission, and yield. We also simulated N management scenarios predicting the magnitude of N losses and yield using Monte Carlo simulations. The meta-analysis revealed that nitrification inhibitors (NI) and urease inhibitors (UI) significantly reduced $NH_3$ volatilization and $N_2O$ emission. Monte Carlo simulations highlighted trade-offs between strategies. The application of dual inhibitors (UI and NI) emerged as the most robust strategy, reducing N losses without incurring a yield penalty. Conversely, scenarios simulating straw removal and reduced N rates illustrated substantial reduction in environmental N losses but also predicted yield decline. These findings suggest that dual inhibitors offer a viable pathway for sustainable intensification, decoupling N loss mitigation from yield penalties. However, relying solely on N rate reduction or residue management requires careful optimization to avoid compromising food security.

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# Water and Nitrogen Management for Intercropping Systems Based on COMSOL Modelling: Crop Growth and Soil Environment

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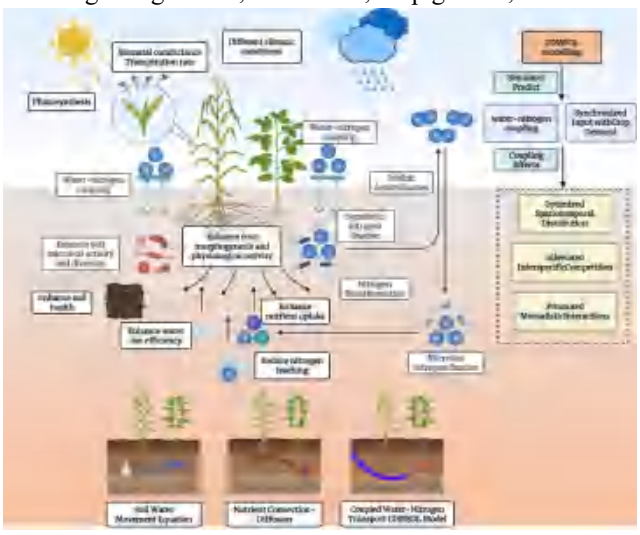
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**ABSTRACT**

Intercropping enhances productivity through species complementarity. In legume-cereal systems, legumes fix nitrogen for cereals while cereals' roots improve soil structure, creating sustainable synergies.This synergistic relationship not only enhances yield stability and nutrient utilization efficiency but also improves soil health and strengthens climate resilience against extreme weather events.Water-nitrogen coupling serves as a fundamental mechanism for regulating intercropping systems. The coordinated interaction between water and nitrogen availability enhances photosynthetic performance, promotes deep root development, and improves both soil water-nitrogen cycling efficiency and rhizosphere microbial community structure. Through precise synchronization with critical crop growth stages, this approach effectively minimizes interspecific competition while reinforcing mutualistic relationships between component crops.The COMSOL Multiphysics simulation platform offers powerful analytical capabilities by integrating soil water transport equations, nutrient advection-diffusion models, and root uptake kinetics. This integrated methodology enables accurate quantification of water and nitrogen migration fluxes at the soil-root interface, reveals fundamental physiological principles governing crop growth responses, and overcomes limitations inherent in traditional experimental approaches for characterizing soil transport processes.This research advances modeling applications to elucidate regionally differentiated effects of water-nitrogen coupling across diverse climate zones and soil types. The findings support the development of precise, regionally adapted water-nitrogen management strategies, thereby providing robust theoretical foundations and effective technical solutions for sustainable optimization of intercropping systems. These advancements contribute significantly to agricultural sustainability and food security objectives across varying production environments.

**Keywords:** intercropping; water-nitrogen regulation; COMSOL; crop growth; soil environment



The multidimensional effects of water-nitrogen coupling in intercropping based on COMSOL Modelling.

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# Exploiting Iron-Efficient Groundnut Genotypes to Combat Iron Deficiency in Calcareous Soils

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**ABSTRACT**

Iron (Fe), though one of the most abundant elements in soils, its deficiency is a worldwide problem in many crops particularly in calcareous soils. The availability of Fe rather than quantity in the soil that affects the growth and development of plants, and has consequence on animals and humans. As effective, economical, and long-term solutions to Fe chlorosis remain limited, the use of Fe efficient genotypes capable of better utilizing native soil Fe offers a promising and sustainable approach.

To select Fe efficient groundnut genotypes for calcareous soil, a pot culture experiment with 20 groundnut genotypes was conducted under Fe-sufficient (+Fe) and Fe-deficient (–Fe) conditions. The soil was sandy clay loam, alkaline in nature with low salinity, high calcium carbonate (12%), low organic carbon (0.23%), and low available Fe (3.85 mg $kg^{-1}$). The genotypes behaviour in terms of morphological, biochemical and yield under +Fe and -Fe application was studied. Based on the data obtained and cluster analysis the genotypes were classified as Fe efficient and Fe inefficient.

Variation was observed in the genotypes under Fe sufficient and Fe stress condition. TAG 24 and VRI 13149 recorded minimum reduction in root length over control (+Fe). The reduction in root volume was minimum with ALR 2 (5.5 %) at vegetative stage and JL 24 (2.3%) at harvest stage. SPAD reading, a parameter closely associated with chlorophyll content of the leaf, varied significantly and minimum reduction in SPAD reading was observed in JL 24 followed by VRI 5.

Catalase, peroxidase activity and active Fe content were highly variable among the genotypes. The genotypes CO7, VRI 8 and VRI 16075 maintained same level of catalase activity both under +Fe and - Fe treatments. Genotypes, TAG 24, CO 7 and JL 24 recorded higher active Fe content under -Fe at vegetative and harvest stage. Release of organic acids, amino acids in the root exudates of groundnut plants especially under Fe stress was observed which could have increased native soil Fe utilization efficiency and ensuring adequate Fe nutrition for the growing groundnut plants. VRI 8 and CO 7 had high response to release of root exudates to the calcareousness condition compared to TMV 7 and VRI 5.

The genotypes TAG 24, CO7, JL 24 and TMV 1 recorded higher Fe content at harvest both under +Fe and -Fe condition. The percentage reduction in Fe content was less than 10 % under -Fe when compared to +Fe. TAG 24 maintained a relatively higher pod yield of 19.9 g $plant^{-1}$ under -Fe.

Based on cluster analysis, the groundnut genotypes, VRI 13149, TMV 2, JL24, TMV 1, TAG 24, CO7, ALR 2, VRI 13113, VRI 8 and VRI 16086 were identified as Fe efficient which can be exploited under calcareous condition to combat Fe deficiency and to increase the Fe Use Efficiency.

**Keywords:** Iron, Efficient, Genotypes, Groundnut

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# Effects of gypsum application on rice growth and yield in paddy soils with varying heavy metal content

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**ABSTRACT**

Sulfur (S) deficiency in paddy rice, characterized by suppressed tillering and the yellowing of lower leaves, has been reported globally. In paddy soils, sulfate-S (available S) is reduced to sulfide-S, leading to the precipitation of insoluble sulfides such as copper sulfide (CuS) and zinc sulfide (ZnS). This suggests that S deficiency may be driven not only by low available S levels but also by an abundance of heavy metals which form insoluble sulfides. However, the effects of gypsum-derived S application on yield, particularly in relation to sulfide formation and heavy metal dynamics, remain insufficiently understood. This study aims to investigate the effects of gypsum application on rice growth and yield in soils with varying heavy metal contents, focusing on the dynamics of S and heavy metals.

A pot experiment was conducted using five paddy soils. The available S content of the tested soils ranged from 8.0 to 46.2 mg $kg^{-1}$. According to Dobermann and Fairhurst (2000), S deficiency is likely when available S is below 9 mg $kg^{-1}$; only one of the tested soils was below this threshold. In contrast, in four of the soils, the concentrations of 0.1 M HCl-extractable metals (sum of Cu, Zn, Pb, Cd, and Ni) exceeded the the available S content. Two S application treatments were applied to each soil, including a control without gypsum (−S) and a gypsum application of 1.5 g $kg^{-1}$ (+S), with four replications. The rice cultivar 'Hitomebore' was cultivated for 126 days. Soil solutions were analyzed for elemental concentrations at regular intervals during the cultivation.

Results showed that the S concentration in the soil solution significantly increased with gypsum application until 42 days after transplanting (DAT). Correspondingly, plant growth in the +S plots was significantly higher than in the −S plots after 42 DAT. The concentrations of Cu and Zn in the soil solution, the dominant 0.1M HCl-extractable metals, decreased as cultivation progressed. Solubility product calculations confirmed indicated that the soil solution became saturated with CuS and ZnS. Gypsum application improved rice yield in all soils; specifically, grain yields increased significantly (by 2- to 38-fold) in the four soils where heavy metal content exceeded available S. Furthermore, a negative correlation was observed between the net difference in (available S minus 0.1 M HCl-extractable metals) and the use efficiency of gypsum-derived S. These results suggest that S fertility in paddy rice depends not only on the S content itself but also on its interaction with heavy metal content.

**Acknowledgments**

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# Spatial distribution of medium and trace elements in tea garden soil of Laoshan District, Qingdao

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**ABSTRACT**

The yield and quality of tea are affected by the soil environment, especially the content of medium and trace elements. Therefore, the abundance and deficiency of medium and trace elements in the soil of the tea garden play a crucial role in the growth and quality of tea. The spatial variation characteristics and effect factors of 7 medium and trace elements (Fe, Mn, Cu, Zn, B, S, Mo) in 0-20 cm and 20-40 cm soil in Laoshan District of Qingdao City were studied by Pearson correlation analysis, single factor analysis of variance and geostatistics, and the current situation of micronutrient content in the soil in Laoshan District was analyzed too. In the study, the available sulfur in 0-20 cm and 20-40 cm soil layers showed strong variation, and other medium and trace elements showed moderate variation. The results of correlation analysis showed that the soil available copper in 0-20 cm and 20-40 cm soil layers were significantly positively correlated with available zinc and altitude. The results of variance analysis showed that altitude had significant differences in the contents of Fe, Cu, Zn, B, S and Mo in 0-20 cm soil layer ($P < 0.05$), while it had significant differences in the contents of Cu, B and S in 20-40 cm soil layer ($P < 0.05$). With the increase of altitude, the soil available copper in 0-20 cm and 20-40 cm soil layers increased with the altitude. The results of semi variance function showed that the soil available iron, available manganese, available copper and available boron were affected by structural factors (topography, parent material, etc.) and random factors (fertilization, tillage, etc.). The order of variation coefficients of seven medium and trace elements in 0-20 cm soil layer were as follows: S > Zn > Cu > B > Mo> Fe> Mn. Moreover, the order of variation coefficients of seven medium and trace elements in 20-40 cm soil layer were as follows: S > Zn > Cu > Mo >B >Mn >Fe. The distribution of available sulfur, available iron and available zinc in soil showed a trend of high level in the South and low in the north of tea garden. The seven medium and trace elements in teagarden of Laoshan were affected by altitude, topography, parent materials and so on.

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# Effect of Manganese Foliar Application in Combination with Bacillus australimaris KU32 on the Stalk Elongation Growth Stage of Sugarcane Variety Khon Kaen 3 Planted in Calcareous Soil

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## ABSTRACT

Sugarcane (*Saccharum officinarum* L.) is an important economic crop in Thailand, known for its high nutrient uptake. Growth and yield reduction may occur under soil conditions, especially in calcareous soils containing high levels of free calcium carbonate and other carbonate salts, affecting the availability of nutrients in the soil. Soil fertilization alone may partially solve this problem. This study investigated the effects of foliar manganese application with *Bacillus australimaris* KU32 on the growth and yield of the sugarcane cultivar Khon Kaen 3 grown in calcareous soils (Khao Phlong soil series: Kpg-hb, cal; coarse-loamy, siliceous, semiactive, isohyperthermic Typic (Kandic) Paleustults. A factorial design in a completely randomized block design with 3 replications was used (2 x 3 Factorial in RCBD, 18 subplots), consisting of two factors. The first factor was bacterial inoculation (non-inoculation and inoculation). The second factor consisted of three levels: a control group without spraying and manganese (manganese sulfate) foliar spray at concentrations of 1% and 2%, respectively. The inoculation was performed simultaneously with the planting process using a sugarcane transplanter, whereas manganese spraying was performed at 2 and 4 months after planting. The experimental plots were located in Nong Krathum Subdistrict, Dem Bang Nang Buat District, Suphan Buri Province (14°52'47.2"N 99°49'16.6"E). Growth data, such as height, stalk number per tiller, leaf greenness, and proline content, were collected every two months until elongation stage. Nutrient content in sugarcane leaves was analyzed at 2, 4, and 6 months after planting. Soil microbial diversity and classification data were collected at 4 and 5 months after planting. The experiment revealed that *Bacillus australimaris* KU32 inoculation exhibited the greatest growth parameters, nutrient accumulation, and microbial diversity of soil compared to non-inoculation. Foliar spray with manganese at 1% concentration is appropriate for plant height, stalk number, and leaf greenness. The findings indicated that sugarcane cultivated in calcareous soils, when treated with a combination of bacterial inoculation and manganese, exhibited the greatest growth and nutrient accumulation compared to all other treatments. Our results will lead to efficient and sustainable plant nutrient management guidelines for sugarcane production in calcareous soil areas.

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# Nanoscale imaging reveals the kinetics of potassium release from biotite and its thermodynamic mechanism

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## ABSTRACT

Soil potassium (K) reserves are abundant, yet the vast majority are structurally bound within minerals, hindering direct uptake by plants. Plants activate mineral K by secreting root exudates that disrupt mineral structures in response to K deficiency stress. However, the microscopic morphological evolution at the mineral-solution interface and the changes in chemical bond energy and potential energy during the release of minerals $K^+$ remain a “black box”. This research investigated the release behavior of minerals K at the microscopic scale and its thermodynamic mechanisms, which is crucial for unlocking soil K resources. The microcosm experiment examined the K release kinetics and biotite morphology changes during its reaction with low-molecular-weight organic acids and biotite under different pH conditions (pH=4, 6, and 8). The mechanism of mineral K release was elucidated by revealing changes in the chemical bond energy of biotite. Results showed that the K and iron (Fe) were preferentially released relative to framework ions silicon [Si], aluminum [Al] during biotite dissolution. The release rates of these metal ions increased significantly with decreasing pH. Atomic force microscopy (AFM) revealed that the initially smooth biotite surface developed pits in the presence of oxalic acid (OA) or citric acid (CA), accompanied by the formation of fibrous precipitates. Raman spectroscopy (RS) was employed to monitor changes in the vibrational modes of biotite bonds. Reaction with organic acids weakened the 105 $cm^{-1}$ peak (assigned to K-O vibrations), facilitating the release of $K^+$ from biotite. Moreover, organic acids attenuated the 675 $cm^{-1}$ peak (Si-O-Si vibrations), which destabilized the mineral framework and promoted biotite dissolution. RS spectra also revealed the presence of peaks characteristic of carboxyl (COOH) functional groups. To investigate how organic acid functional groups influence mineral dissolution and K release, dynamic force spectroscopy (DFS) was used to quantify changes in the binding energy between hydroxyl (–OH) and –COOH groups and the biotite surface. As the pH of the microcosm decreased from 6 to 4, the binding energies increased from 7.0 to 10.3 kJ $mol^{-1}$ for –OH, and from 4.2 to 8.5 kJ $mol^{-1}$ for –COOH. Low-molecular-weight organic acids weakened the framework stability of biotite and disrupted its morphological structure by lowering the pH of the microenvironment and promoting the adsorption of organic functional groups onto mineral surfaces. It caused disorder in the K coordination environment and promoted the release of $K^+$ by reducing their binding strength.

**Key word:** Mineral potassium release; Mineral dissolution; Functional group; Proton action; Chemical bond.

# Balanced NPK Nutrition via TNAU-Water Soluble Fertilizer for Higher Yield and Nutrient Efficiency in Cotton

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**ABSTRACT**

Balanced nutrition is critical for achieving higher yield and better nutrient efficiency in cotton. Nitrogen, phosphorus and potassium play complementary roles in crop growth and their balanced supply ensures optimal vegetative growth, reproductive development and boll formation. Water soluble fertilizers are designed to dissolve completely in water, releasing nutrients that are immediately available for plant uptake. This facilitates rapid absorption by roots and/or foliage, helps synchronize nutrient availability with crop demand and reduces losses associated with leaching, volatilization, fixation, or immobilization in the soil. As a result, water soluble fertilizers generally exhibit higher nutrient efficiency and more precise delivery compared with conventional soil-broadcast granular fertilizers.

Field experiments were carried out to evaluate the influence ofTNAU -Water Soluble Fertilizer (WSF) on seed cotton yield and nutrient efficiency in cotton (Variety CO 17). The experiment comprised graded levels of NPK (0, 25, 50, 75, and 100%) as main plot treatments and different levels of TNAU-WSF (0, 20, 40, 60 kg $ha^{-1}$ and 1% foliar spray) as subplot treatments. The study was conducted in strip plot design with two replications. The experimental soils were analyzed for initial nutrient status, and graded levels of NPK were applied based on the Soil Test Crop Response (STCR) approach, targeting a yield of 30 quintals per hectare. Biometric parameters such as plant height, number of branches and leaf area index were recorded. Seed cotton yield, nutrient uptake and nutrient efficiency were also assessed. The results revealed that application of 100% STCR-NPK along with TNAU-WSF @ 40 kg $ha^{-1}$ through fertigation recorded the highest biometric values, including plant height (128 cm), number of primary branches (25), leaf area index (4.8), number of bolls per plant (25.1) and seed cotton yield (3189 kg $ha^{-1}$). These results were statistically comparable with 75% STCR-NPK + TNAU-WSF @ 40 kg $ha^{-1}$. However, the maximum net profit (3.18) and nutrient efficiency (N: 81.9%, P: 67.4%, and K: 80.7%) were observed with 75% STCR-NPK combined with TNAU-WSF @ 40 kg $ha^{-1}$. To conclude, application of 75% STCR-based NPK + TNAU -WSF @ 40 kg $ha^{-1}$ is recommended for achieving higher seed cotton yield, improved nutrient efficiency and enhanced economic returns.

**Key Words:** TNAU-Water soluble fertilizer, Crop yield parameters, Seed cotton yield, Efficiency of nutrient utilization

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# Modelling the effect of soil nutrient and carbon mitigation measures in European agriculture

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**ABSTRACT**

Soil nutrient imbalances can have negative impacts on the environment and crop yield. Across the globe, policies are made to improve agricultural sustainability. This study focusses on the policy goals set by the European Union. Trade-offs and synergies can occur when implementing nutrient and carbon measures to improve soil quality, water quality, crop productivity, and biodiversity, and to reduce GHG emissions. Unfortunately, there is little known about trade-offs and synergies when these measures are applied. This study evaluates the potential effect of nutrient and carbon measures along these five goals. Because of this integrated approach, policymakers can make substantiated decisions on the adoption or stimulation of mitigation measures to reconcile agronomic and environmental objectives. The deterministic emission and nutrient flow model MITERRA-Europe model was used to evaluate the measures at regional level for EU-27, the United Kingdom and Switzerland (Duan et al., 2025). This model evaluates a wide range of nutrients (N, P, K, S, Ca, Mg, Zn, Cu) that are important for plant growth and soil fertility, but when applied inappropriate, they can also harm the environment. The model also evaluates the turnover of soil organic carbon, based on the RothC model, and its interactions with soil organic nitrogen. First, the current and desired soil nutrient and carbon budgets, i.e. difference between inputs and outputs, were assessed to understand the gap that needs to be bridged. Secondly, the effect of a series of mitigation measures was evaluated, summarized in ten roadmaps. Depending on the prioritized goal and focus area, one or multiple objectives could be achieved, underpinning policies on site specific management to reach the desired objectives. These roadmaps will soon become available on the NutriPlatform, i.e., a platform that was built as part of the NutriBudget project (Grant agreement ID: 101060455). This platform serves as a decision support tool for multiple stakeholders, because it includes also an interactive farm-level tool (i.e., NutriFarm).

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# Calibration and Validation of a Site-Specific Nutrient Expert Tool for Sorghum in the Sudano-Sahelian Region of Nigeria

**ABSTRACT**

Low soil fertility and inadequate nutrient management severely constrain sorghum productivity in the Sudano-Sahelian region of Nigeria, undermining food security. Blanket fertilizer recommendations fail to account for the high spatial variability of soil nutrient status, resulting in suboptimal yields and inefficient fertilizer use. To address this challenge, we developed and validated a site-specific Nutrient Expert (NE) tool for sorghum using the QUEFTS model framework.

The NE tool was calibrated using data from 60 on-farm nutrient omission trials (NOTs) conducted during the 2020 rainy season across 12 Local Government Areas in four states. Forty-six fields (76%) were randomly selected for calibration, while 14 fields (24%) were reserved for validation. Yield responses to nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) were calculated from NPKS and nutrient omission treatments. Nutrient requirements were estimated using agronomic efficiency for N and recovery efficiency indices for P, K, and S. Spatial soil data at 5×5 km resolution from ISRIC and iSDA databases were used to generate location-specific recommendations based on soil nutrient supply indices.

The calibrated tool produced spatially variable nutrient recommendations: N requirements ranged from 24 to 75 kg/ha (mean 55–75 kg/ha in most areas), P from 17 to 41 kg $P_2O_5$/ha (mean 26–41 kg/ha), K from 12.6 to 25.7 kg $K_2O$/ha, and S from 0 to 31 kg/ha (mean 0–6 kg/ha in most areas). Attainable yields ranged from 2,879 kg/ha in Bauchi State to 3,127 kg/ha in Katsina State. Model validation using the reversed QUEFTS approach on the independent validation dataset yielded an $R^2$ of 0.53 for the relationship between observed and predicted yields, indicating fair predictive performance. The model's precision is expected to improve significantly with ground-based field soil test data.

To facilitate widespread adoption, a user-friendly web-based platform was developed that enables farmers and extension agents to generate customized fertilizer recommendations by selecting their location and inputting farm management data. The platform translates model outputs into practical fertilizer product equivalents and application guidelines consistent with 4R Nutrient Stewardship principles.

The Sorghum NE Tool represents a significant advancement in decision support for smallholder farmers in the Sudano-Sahelian region. By providing accessible, science-based, and site-specific fertilizer recommendations, it offers a scalable pathway to enhance fertilizer use efficiency, improve sorghum yields, and strengthen regional food security. Future work will focus on transitioning to a scalable API-driven architecture, and integrating real-time climate data.

# Paddy-Upland Rotation in Southern China's Red-Yellow Soils: A Meta-Analysis Reveals Short-Term Benefits and Long-Term Risks

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## ABSTRACT

Paddy-upland rotation is widely regarded as an effective strategy to overcome obstacles associated with continuous rice monoculture. Compared with the conventional long-term flooded rice cropping system, this approach not only significantly enhances grain yield and quality but also improves overall soil health and enhances microbial diversity and activity. Along with socioeconomic development, cropping systems in the red-yellow soil regions of southern China have undergone substantial transformation. While traditional double-rice cultivation has declined, paddy-upland rotation has expanded rapidly; however, its system-level impacts on soil quality and crop productivity remain insufficiently understood.

This study employed a meta-analysis to systematically examine the effects of paddy-upland rotation systems—focusing on rotation duration and regional factors—on soil quality and crop yield in this region. Results indicate that during the initial five-year period, compared to continuous flooded cultivation, rotation significantly enhanced soil fertility and rice yield: soil pH significantly increased, bulk density decreased by 5.3%, and total nitrogen, total phosphorus, available nitrogen, available phosphorus, and available potassium showed significant increases ranging from 5.3% to 21.1%. These changes help mitigate the typical nitrogen, phosphorus, and potassium deficiencies in red-yellow soils. However, when extended beyond five years—particularly over fifteen years-rotation leads to soil acidification and depletion of available nitrogen and available potassium reserves, which may ultimately constrain crop growth and yield. These adverse effects were most pronounced under the double rice-rapeseed rotation system. Regional analysis revealed that in Hunan Province, where double rice-rapeseed rotation predominates, soil organic matter, available nitrogen, and available potassium decreased significantly, with reductions ranging from 10.5% to 22.1%. Fertilization management played a critical role in modulating system outcomes: moderate nitrogen application significantly improved nutrient availability and grain yield, whereas excessive nitrogen (>360 kg/ha) exacerbated acidification and reduced the availability of nitrogen, phosphorus, and potassium.

In summary, while short-term paddy-upland rotation can improve soil quality, particularly by enhancing nitrogen-phosphorus availability in red-yellow soil regions, long-term practice without amendments accelerates acidification. Sustaining soil productivity and rice yields requires site-specific optimization of rotation sequence, duration, and nutrient management.

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# Vegetation types and management practices reshape mineral element cycling in tropical soil–plant systems

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**ABSTRACT**

Land-use change and intensive agricultural management in tropics are altering biogeochemical cycling within soil–plant systems. Understanding mineral element cycling under different vegetation types and management practices is essential for sustaining soil fertility and preventing nutrient depletion. To explore the relative roles of vegetation types and agricultural management in element cycling, we investigated four vegetation types on Hainan Island, China, including natural forest, rubber, banana, and paddy field. Through two-year monitoring of throughfall, irrigation, runoff, and plant organs, we quantified the budgets of Si, K, Ca, Na, and Mg. Canopy leaching influenced throughfall inputs. K showed stronger canopy leaching, and Si leaching correlated positively with leaf Si content. Management altered element budgets by regulating inputs and outputs. Banana showed net accumulation, while plant uptake accounted for only 39% of external K inputs. In paddy fields, harvest resulted in a Si deficit of 365 kg $ha^{-1}$ $yr^{-1}$. Rubber showed net Mg losses due to NPK-dominated fertilization and latex tapping. Element cycling efficiency (ECE) revealed mechanisms of element imbalance. Low ECE in rubber (44%) resulted in insufficient litterfall inputs to offset runoff losses. Banana exhibited high ECE (85%), but excessive inputs from fertilizer caused element accumulation. In paddy fields, K and Ca cycled efficiently, while Si was depleted due to harvest. Natural forest maintained balance for most elements through moderate ECE (61%). This study reveals that agricultural management overrides vegetation types as the dominant driver of element cycling. Future management should prioritize integrated strategies centered on element balance to achieve soil productivity.

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# Trends and geographic variation in adverse impacts of nitrogen use in Europe on human health, climate, and ecosystems: A review

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**ABSTRACT**

Human activities have greatly increased the loss of reactive nitrogen compounds, especially of nitrogen oxides ($NO_x$), ammonia ($NH_3$), nitrous oxide ($N_2O$) and nitrate ($NO_3$), to air and water. This review assesses the impacts of trends in reactive nitrogen use on air, soil, and water quality across Europe from 1990 to 2019, focusing on temporal trends and spatial patterns. The analysis is based on long-term monitoring data and air quality modelling using the EMEP model, and evaluates consequences for human health, terrestrial and aquatic ecosystems, and climate change. Ecological and health risks are quantified by examining exceedances of critical nitrogen levels and loads.

Over the studied period, emissions of nitrogen oxides ($NO_x$) and ammonia ($NH_3$) declined substantially, by 57% and 27% respectively. Despite this, atmospheric $NH_3$ concentrations slightly increased, largely due to reduced sulfur emissions. Improvements in ozone-related indicators and ecosystem exposure were limited. Nitrogen deposition and exceedances of critical loads in terrestrial ecosystems decreased by about 60%, yet the total area affected declined by only 10%, indicating persistent pressure on sensitive ecosystems. Groundwater nitrate concentrations remained largely stable across Europe, while nitrogen levels in rivers, lakes, and coastal waters generally declined. However, eutrophication continues in many coastal areas, partly driven by high phosphorus inputs. Overall, nitrogen pollution hotspots remain, especially in regions with intensive agriculture and high population density.

The review also evaluates the economic dimensions of reactive nitrogen use, concluding that environmental and health costs exceed the economic benefits of agriculture. While nitrogen is essential for food production, more efficient and integrated nutrient management is needed to reduce losses. The study highlights the importance of reducing nitrogen emissions throughout the entire food supply chain, in line with the EU Farm to Fork Strategy, which aims to cut nutrient losses by 50% by 2030.

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# Potassium Management Strategies for Soybean–Corn Rotation Under No-Tillage in a Brazilian Oxisol

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**ABSTRACT**

Efficient fertilizer management involves selecting the appropriate source, rate, timing, and placement to ensure nutrient availability for plant uptake while minimizing environmental losses. This study evaluated the effects of different rates, timings, and placements of potassium (K) fertilizer on a soybean–corn (*Glycine max* L. – *Zea mays* L.) rotation, starting with soybean, under a no-tillage system in a sandy soil (Cerrado) in Brazil. The experiment was conducted over eight consecutive growing seasons in a well-established area with a history of consecutive soybean and corn cultivation and previously built soil fertility**.** The following annual treatments were applied to both crops:0P0K (control without P and K); 0K (fertilization without K); 100F (100% K in the planting furrow); 100T (100% K as topdressing post-emergence); 50S/50T (50% K at planting + 50% as topdressing, both surface-applied); 50S (50% K at planting, surface-applied); 100S (100% K at planting, surface-applied); and 100F/50T (100% K in the furrow + 50% as topdressing). Grain yield, agronomic efficiency, and the partial K balance were determined. Data were subjected to Bartlett's and Shapiro-Wilk tests ($p < 0.05$) to verify variance homogeneity and residual normality, respectively. ANOVA was performed, and means were compared using the Scott-Knott test ($p < 0.05$). No significant differences were observed among treatments during the first soybean crop. However, the 0P0K treatment resulted in lower yields in the first corn crop, indicating P deficiency preceded K deficiency. Starting from the second soybean crop (the third harvest analyzed), surface K applications led to higher yields than furrow applications, with no significant effect of application timing. Applying half of the recommended K rate on the surface was effective in the short term but resulted in a negative K balance, potentially compromising soil fertility over time. Surface application of the full recommended K rate at planting is the most effective strategy for soybean-corn rotations in sandy soils of Western Bahia, Brazilian Cerrado, promoting higher productivity and long-term maintenance of soil fertility.

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# Simultaneous aerobic stabilisation of sewage sludge and chelator-assisted removal of toxic metals in a closed-loop process

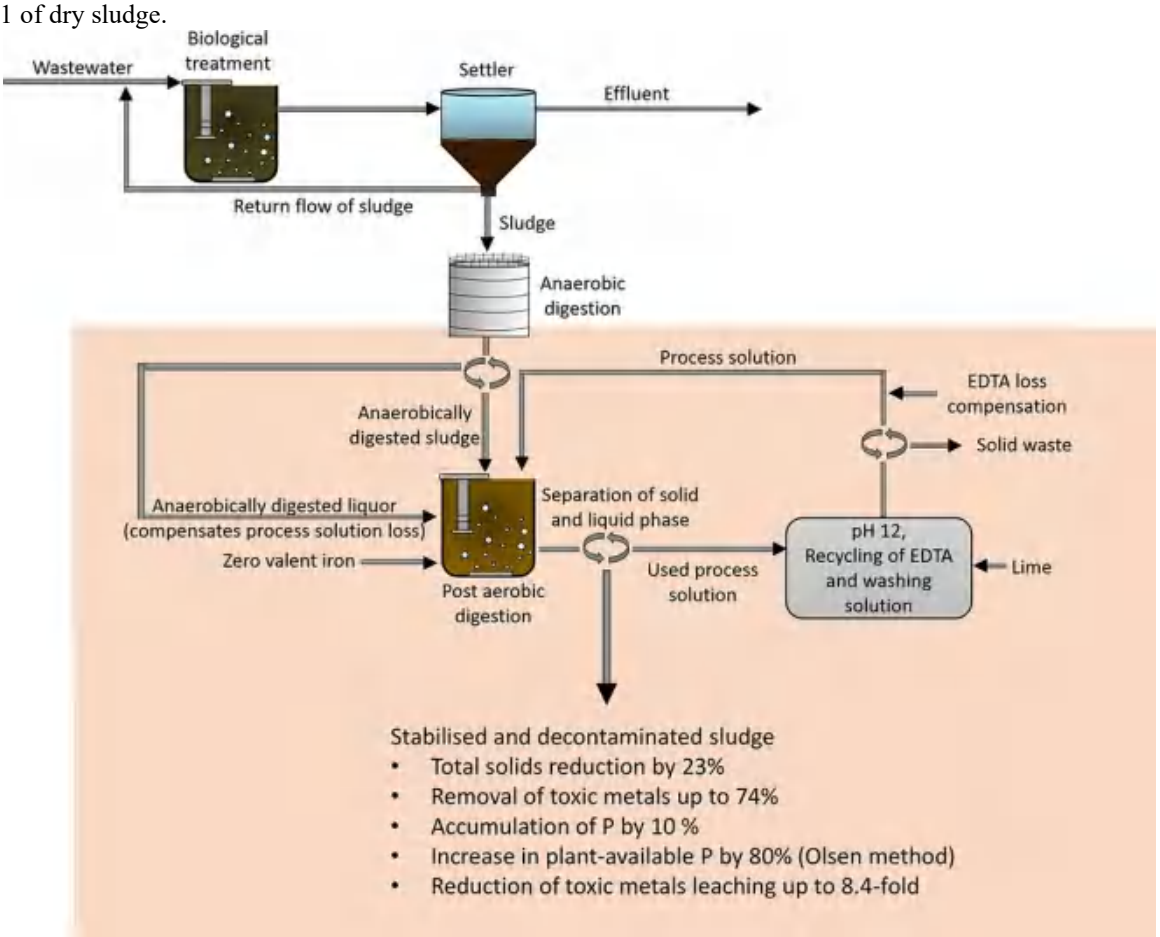
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## ABSTRACT

Sewage sludge is a valuable source of phosphorus but contains toxic metals that hinder its use as fertilizer. We present a novel process that simultaneously stabilises sludge through post-aerobic digestion (12 days, pH 5.8–7.6, solid-to-liquid ratio 1:25 (dry w/v)) and removes toxic metals using ethylenediaminetetraacetate (EDTA, 10 mM). On average, 74.4% of EDTA was successfully recycled by alkalinization of process solution with quicklime (CaO) to pH 12.5 and reused in subsequent batches. Chelator losses were compensated by the addition of Na-EDTA. Toxic metals, along with excess Ca and Na, were effectively removed from the recycled process solution, enabling closed-loop operation without wastewater generation. During five consecutive batches, total solids in the sludge were reduced by an average of 23.2%, and 74, 61, 26, and 43% of Zn, Cu, Cr, and Pb, respectively, were removed. The leaching of residual toxic metals from the stabilised and decontaminated sludge was further reduced by 55–88% through the addition of zero-valent iron (3% dry w/w). The process also increased the phosphorus concentration in the sludge by 15% and improved its phytoavailability up to 1.8-fold (as determined by ammonium-lactate extraction). This process is sustainable: it preserves valuable nutrients, can be integrated into existing wastewater treatment plant operations, generates only 17% solid waste (relative to the dry weight of the sludge), and produces no wastewater. Due to the recycling of costly EDTA, reagent costs were halved, reaching €73 t-1 of dry sludge.



# Blended Amendments to Reduce Soil Phosphorus Solubility and Mitigate Phosphorus Loss with Snowmelt Flooding

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## ABSTRACT

Spring snowmelt flooding is a major pathway of phosphorus (P) loss from croplands in cold regions such as the Canadian prairies, posing a threat of eutrophication to freshwater bodies. The beneficial management practices commonly adopted to minimize P losses due to soil erosion and rainfall runoff (e.g., conservation tillage) have often led to an increase in dissolved P losses with snowmelt, particularly in non-erodible flat landscapes. Thus, alternative P loss mitigation strategies are needed for cold, flat regions where P loss is dominated by snowmelt runoff. The application of soil amendments is a strategy to decrease soluble P in surface soils, thereby reducing losses. Since a range of soil- and amendment-specific mechanisms are responsible for reducing P loss, blended amendments are a more effective approach than applying a single amendment. We evaluated gypsum ($CaSO_4.2H_2O$) and ferric chloride ($FeCl_3$) applied singly (2.5 Mg $ha^{-1}$), or as a 1:1 blend (2.5 Mg $ha^{-1}$ of each) on soil P solubility and P release from flooded soil under cold conditions in packed and intact soil columns. To investigate the amendment effects on P solubility, six soils collected from agricultural fields in Manitoba, Canada, were treated with gypsum, ferric chloride, or their blends, and incubated at room temperature with an unamended control and analyzed for water extractable P (WEP) at 0, 28, and 84 days. To investigate the amendment effects on P release under simulated snowmelt conditions, packed (same six soils) or intact soil columns (four selected soils) were amended with gypsum, ferric chloride, or their blends, flooded with ultrapure water, and incubated at cold temperatures (+4 °C) for 56 days. Floodwater samples collected bi-weekly were analyzed for dissolved reactive P (DRP) concentrations. Both single and blended amendment treatments significantly reduced WEP in soils compared to the unamended control, with blended amendment treatment showing a superior impact than single amendments. In the packed soil column study, blended amendment resulted in greater DRP reductions in floodwater, with an 87% decrease in DRP concentration at 56 days, compared to 64% and 46% reduction with ferric chloride and gypsum, respectively, applied alone. In the intact soil column study, the decrease in DRP concentration in floodwater of intact soil columns ranged from 31 to 56% for gypsum, 93 to 99% for ferric chloride, and 95 to 98% for blended amendment, with no significant difference between single amendment of ferric chloride and blended gypsum-ferric chloride treatments. Our results suggest that amendment blends can be more effective in reducing P loss from soils with snowmelt flooding; however, the long-term impacts of amendment applications need to be investigated in the field under varying environmental conditions.

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# Soil Phosphorus dynamics in a Vertosol with a long cropping history

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**ABSTRACT**

Improving soil phosphorus (P) availability is critical for crop productivity, as only 0.1-0.5% of total soil P is readily available to plants. In the grain production regions of northeast Australia, this is particularly important on the alkaline Vertosols in which high calcium availability restricts P solubility. The study aimed to understand the fate and dynamics of fertiliser-derived P in a Vertosol under cultivation for 36 years in the Colonsay long-term field experiment, focusing on the accumulation, transformation, and mobility of P across depths and soil P pools. The study used soil from four long-term treatments: 0N 0P, 0N 20P, 80N 0P, and 80N 20P, with soil P availability assessed using intensity, quantity, and buffer capacity factors. Samples from the topsoil (0–10 cm) and subsoil (10–30 cm) were analysed using BSES, NaOH-EDTA, and ignition-$H_2SO_4$ extraction to quantify P pools. Sorption-desorption kinetics and isotope exchange kinetics (IEK, $^{32}PO_4$–$^{31}PO_4$ exchange under steady-state conditions) were employed to evaluate P binding and release dynamics. Results showed that approximately 30% of applied P accumulated in the topsoil, primarily within moderately to sparingly labile pools, with NaOH-EDTA and BSES extractions accounting for 56% and 53% of total P, respectively, under fertilised conditions. Subsoil P concentrations also increased with fertilisation but remained lower than in the topsoil, indicating P uptake from deeper layers where soil moisture persists for longer. Long-term fertilisation reduced P sorption capacity, lowered hysteresis ratios, and enhanced desorption, thereby improving P mobility and availability. Conversely, unfertilised soils exhibited higher buffering capacity and limited P release potential. These findings demonstrate that fertiliser history modifies soil reactive surfaces and the behaviour of legacy P. Overall, surface-applied P fertilisers appear ineffective in improving crop P availability in Vertosols used for rainfed cropping, whereas deep banding in the subsoil may enhance P use efficiency and long-term sustainability.

# Fungal-mediated synergy between nitrogen fixation and phosphorus acquisition in a maize-lablab mixture

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**ABSTRACT**

The productivity of legume-cereal intercropping systems is largely governed by symbiotic nitrogen fixation (SNF) and phosphorus (P) mobilization. Yet, how these processes interact synergistically to drive N and P facilitation remains poorly understood. Through a factorial experiment manipulating N level, P form, and root separation in a lablab-maize mixture system, we assessed plant nutrient, root traits, and microbial communities. We found that SNF in lablab was strongly correlated with tissue P concentration. Strikingly, structural equation modeling identified a direct, bidirectional reinforcement: shoot Ndfa was the strongest predictor of shoot P accumulation ($\beta$=0.52, $p<0.01$), and vice versa, shoot P was the strongest predictor of shoot Ndfa ($\beta$=0.55, $p<0.001$). Mixture (under mesh and no barrier) reduced the optimal N application rate for maize by around 50%, underscoring a significant N-saving effect. Compartment-specific fungal community mediated this synergy: under N amendment, lablab rhizosphere fungi correlated with maize soil nitrate ($NO_3^-$) (mesh) or specific root length (no barrier), while under P amendment, maize rhizosphere fungi were associated with lablab shoot Ndfa (mesh) or soil $NO_3^-$ (no barrier). These findings establish a novel paradigm of direct legume-mediated N–P coordination, positioning fungal communities as central hubs orchestrating nutrient synergies in cereal-legume systems.

**Keywords:** Organic acid anions, Flavonoid, Mycorrhizal infection rate, Acid phosphatase, Alkaline phosphatase, Root morphology

**Acknowledgments**

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# Differential contributions of rare and abundant phosphate-solubilizing bacteria to organic phosphorus mineralization under long-term fertilization

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**ABSTRACT**

Phosphorus (P) is a major limiting nutrient for crop production in many agroecosystems. Phosphorus-solubilizing microorganisms (PSMs) play crucial roles in mobilizing fixed soil P by secreting P-mineralizing enzymes such as acid phosphatase (ACP) and alkaline phosphatase (ALP). Fertilization, as a key anthropogenic disturbance, significantly shapes the diversity and composition of PSM communities, thereby influencing soil P mineralization. However, the responses of *phoC*- and *phoD*-harboring bacterial communities to different fertilization strategies, as well as the relative contributions of rare versus abundant taxa to P cycling, remain poorly understood. This knowledge gap hampers the development of microbiome-based solutions for sustainable agriculture.

In this study, we conducted a long-term fertilization experiment in the North China Plain, comparing organic manure and mineral fertilizer treatments with equal nutrient inputs. We assessed soil properties, phosphatase activities, and the diversity and assembly processes of *phoC*- and *phoD*-harboring bacterial communities. Organic fertilizer significantly enhanced ACP and ALP activities and altered the microbial community structure. Although rare taxa exhibited low relative abundance, they contributed disproportionately to community diversity and functional regulation, particularly under organic fertilization. Our results revealed distinct mechanisms underlying the contributions of *phoC*- and *phoD*-harboring communities. The diversity and network structure of rare *phoC* taxa were strongly associated with ACP activity and were primarily driven by species substitution processes. In contrast, the composition and function of *phoD* communities, particularly among abundant taxa, were mainly regulated by indigenous microorganisms. These contrasting mechanisms highlight the ecological significance of rare taxa and demonstrate that *phoC* and *phoD* communities contribute to soil P mineralization through different regulatory modes.

Collectively, this study provides novel insights into the functional roles of rare and abundant microbial subcommunities in soil P cycling. By uncovering the divergent regulatory mechanisms of *phoC* and *phoD* communities under fertilization, our findings offer a scientific basis for developing sustainable fertilization strategies and improving soil–plant health.

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# Scale-dependent limitation of the Mehlich-3 method for evaluating soil phosphorus across heterogeneous paddy soils in Japan

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## ABSTRACT

The Mehlich 3 extraction (M3) is a high-throughput evaluation method for macronutrient availability in soils. Although M3-extractable amounts of exchangeable bases are generally comparable to those obtained by conventional extractions, notable discrepancies between the two approaches—particularly for phosphorus—have also been documented. These discrepancies tend to increase when mineralogical composition varies substantially among samples. In Japan, the dominant factor driving such variability is the influence of volcanic ash deposition on soil development. Therefore, we hypothesized that discrepancies between M3 and conventional extractions would be amplified in large-scale datasets encompassing paddy soils with contrasting degrees of volcanic ash influence. To test this hypothesis, we compared the Mehlich 3 method with conventional extractions using a multi-scale dataset of Japanese paddy soils to assess the reliability of converting M3-derived phosphorus and exchangeable bases. A total of 300 soil samples were collected across Japan, and classified into Local (n = 60), Regional (n = 145), and National (n = 95) scale datasets. The variability of physicochemical properties decreased with decreasing spatial scale, especially acid-oxalate extractable elements. Phosphorus and three base cations (Ca, Mg, K) were extracted either with the Mehlich 3 method or conventional methods; Bray 2 and Truog for P and ammonium acetate for base cations. Although the M3 method provided consistent extractability for exchangeable bases ($R^2 > 0.87$), its correspondence with conventional P extractions was weak when all soil samples were analyzed regardless of their spatial origin (Bray 2: $R^2 = 0.62$, Truog: $R^2 = 0.35$). Stratifying the dataset by spatial scale markedly strengthened their relationships as spatial scale narrowed, yielding strong linear correspondence at the Local scale (e.g., Bray 2: Fig.1). To identify the factors responsible for low correspondence at broader scales, we quantified the divergence as the ratio of P extracted by each conventional extraction to the M3 (Bray 2/M3 and Truog/M3) and performed multiple regression analysis using soil physicochemical properties as explanatory variables. The analysis identified amorphous Fe and Al (hydr)oxide contents ($Fe_o$ and $Al_o$) as the primary predictors controlling the divergence between M3-P and both conventional extractions ($p < 0.001$), indicating that their variability largely governed the divergence in P extractability between the methods. Overall, these findings indicate that the M3 method enables high-throughput evaluation of macronutrient availability in settings where the variability of amorphous Fe/Al (hydr)oxides is limited, such as local-scale domains. This study highlights the importance of recognizing mineralogical variability in the target dataset for achieving accurate nutrient evaluation and developing precision nutrient-management strategies in paddy soils with heterogeneous pedogenic settings.

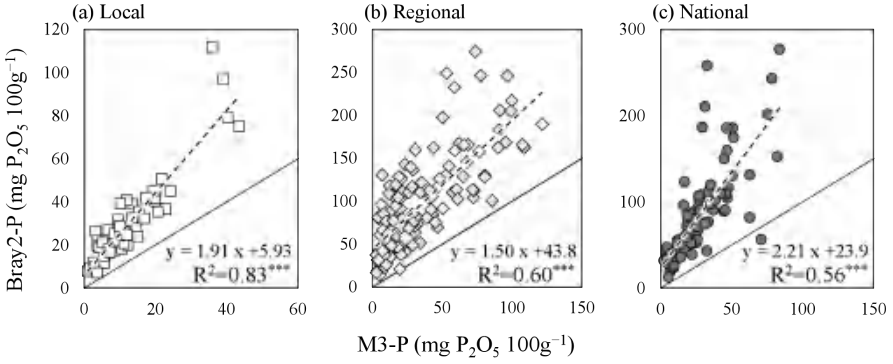



Fig. 1 Variation in the relationships between the Mehlich 3 and Bray 2 methods across spatial scales

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# Soybean-cotton rotation and soil phosphorus dynamics under long-term management and cover crops

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**ABSTRACT**

Phosphorus (P) is one of the limiting nutrients for agricultural production in the tropics due to its high rates of adsorption and precipitation in the soil. The cultivation of cover crops associated with conservation management systems can enhance the efficiency of P use. Therefore, this study aimed to evaluate the accumulated yield of soybean and cotton in rotation and the changes in soil P dynamics promoted using cover crops and different soil management systems in three long-term experiments established in the Brazilian Cerrado. The treatments consisted of: two management systems (conventional tillage - CT and no-tillage - NT), three cover crops (pearl millet, ruzigrass and crotalaria) and a fallow. The cumulative yield of soybeans and cotton (Mg $ha^{-1}$) and changes in soil P fractions (0-5, 5-10, 10-20 and 20-30 cm) were determined after more than 15 years of cash crop/cover crop rotation. Cover crops, especially ruzigrass, increased soybean and cotton yields in the long term by up to 13.37 and 19.65%, respectively. In general, fallow and CT contributed to increasing the levels of labile P in the soil, while grasses (ruzigrass and pearl millet) reduced the less labile fractions of P. Our results indicate that the long-term use of cover crops increases the yield of cash crops. In addition, these plants can temporarily immobilize P in their biomass and access the less available forms of P in the soil, thus promoting legacy P cycling.

**Keywords:** Tropical soils; Soybean and cotton productivity; P dynamics; Chemical P fractionation; crop rotation

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# Phosphorus sorption in acidic soils following the application of Calciprill and sodium silicate

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## ABSTRACT

In highly weathered acidic soils (pH<5.5), the phosphate ions ($HPO_4^{2-}$ and $H_2PO_4^-$) released from the phosphorus (P) source fertilizers tend to adsorb with the hydrolyzed aluminium ($Al^{3+}$) and iron ($Fe^{2+}$) in the soil solution, thus reducing P uptake and use efficiency by the plants. The use of Calciprill and sodium silicate can release of calcium ($Ca^{2+}$) and silicon (Si) ions to increase the pH of acidic soils and transform the active $Al^{3+}$ and $Fe^{2+}$ into insoluble hydroxides, thus changing the P adsorption behaviour in soils. A phosphate sorption study was conducted to elucidate the effects of Calciprill and sodium silicate on P sorption behaviour in an acidic soil (Bekenu series, *Typic Paleudults*). Four treatments were evaluated: (i) soil only without any amendment (S0); (ii) soil + Calciprill at 100% calcium saturation (C100); (iii) soil + sodium silicate at 150 kg $ha^{-1}$ (S150); and (iv) soil + Calciprill + sodium silicate (C100+S150). The P adsorption capacity was determined through the addition of P isonormal solutions at 250, 500, 750, and 1000 mg $L^{-1}$ P by establishing a linear relationship between the amounts of P adsorbed and left in the equilibrium solution. The collected data were fitted to Langmuir and Freundlich isotherms to reveal the P adsorption behaviour in the treated soils. The same soil samples were added with 0.01 mol $dm^{-3}$ calcium chloride to desorb the phosphate ions. Results revealed that C100+S150 significantly improved P adsorption compared with C100, whereas the insignificant difference in the amount of P adsorbed for S150 and S0 suggests that Calciprill dominantly increased P adsorption. It was observed that the P adsorption in S0, C100, and C100+S150 followed the Langmuir isotherm, whereas S150 followed the assumptions of Freundlich isotherm, indicating that the use of different amendments can influence P adsorption behaviour. For P desorption, the significantly higher P desorption in S150 was due to the higher affinity of water-soluble Si to mobilize P from the soil minerals, whereas lower P desorption in C100 was due to P fixation by the Calciprill temporarily as Ca-phosphate. These findings indicate that Calciprill can reduce P losses, whereas sodium silicate can release available P for crop uptake.

**Acknowledgments**

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# Tracking of residual soil phosphorus pools using phosphate oxygen isotopes

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**ABSTRACT**

Excess phosphorus (P) loading has led to eutrophication and deteriorated the water quality globally. The existing limitation of analytical methods for tracing residual and recalcitrant P pools has posed a challenge to discern specific sources, specifically legacy sources, which are considered the missing piece of the global P puzzle. In this study, residual P pools of soils and sediments from the East Creek micro-watershed in the Chesapeake Bay watershed were sequentially extracted using 10 M $HNO_3$, 10 M NaOH, and aqua regia, and phosphate oxygen isotopes ($\delta^{18}O_P$) of these soil P pools were then measured. Additionally, the isotope integrity of each reagent was
assessed and found that 10 M $HNO_3$ and 10 M NaOH do not significantly compromise the original isotope values over the extraction time. The isotopes of inorganic residual soil Pi pools revealed a distinct range of isotope values among different land uses as well as specific landforms within each land use, suggesting the usefulness of isotopes of residual Pi pools to discriminate different P sources in sub-land uses. Furthermore, isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) of residual soil pools showed distinct signatures among sources and pointed to potential signals imprinted from the past cropping systems. Contributions of soils from wetland, streambank, agricultural
land, and forest sources varied systematically along East Creek. The Bayesian elemental fingerprinting model provided the effect of the dynamic nature of sources, as well as potential creek meanders. In conclusion, the integration of multi-isotope and elemental fingerprinting methods of residual soil P pools presents a promising and complementary tool for tracking sources in watersheds.

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# An insight on best management practices for phosphorus fertilization in cereal-based cropping systems

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**ABSTRACT**

Phosphorus (P) deficiency is a major constraint to crop productivity and grain nutritional quality in cereal-based cropping systems worldwide. Moreover, unsustainable P management increase the risk of P accumulation in soils and subsequent transfer to surface waters. Enhancing phosphorus use efficiency (PUE) is therefore critical to simultaneously address agronomic, environmental, and resource-security challenges associated with P management. Effective and responsible P stewardship requires a comprehensive understanding of P dynamics within the soil–plant system and must be adapted to soil properties, climatic conditions, cropping system characteristics, and management intensity. Best management practices (BMPs) encompass not only fertilizer strategies but also crop and rotation management, soil acidity management, nutrient interactions, conservation tillage, assessment of off-site P loss risk, and farm-level economic and logistical factors. The 4R nutrient stewardship framework (right source, rate, time, and placement) provides a scientifically grounded approach for optimizing fertilizer use (IPNI, 2016). A wide range of P sources is currently available, including conventional mineral fertilizers, novel P formulations, organic amendments, and recycled products such as manure, sewage sludge, and food-processing wastes. These alternative sources require rigorous evaluation under laboratory, greenhouse, and field conditions to support science-based recommendations.

Selection of appropriate P rates is fundamental not only for maximizing crop response but also for managing P residual effects and minimizing environmental losses. Soil testing remains the principal tool guiding P fertilization decisions across most agricultural regions. A variety of fertilizer placement methods—seed-banding, side-banding, deep banding, and broadcasting—are used in cereal systems, and their effectiveness can be further enhanced through site-specific management and precision-agriculture technologies.

Timing of P application depends on soil P dynamics, crop requirements, and P source/placement. Given the low mobility of P in soils, applications are often made before planting to ensure adequate early-season P supply, a key determinant of yield potential and PUE.

Collectively, fertilizer BMPs constitute the foundation for sustainable P management in cereal-based cropping systems, contributing to improved P recovery and recycling in the soil, mitigation of environmental impacts, and long-term P resource sustainability.

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# Managing Legacy Phosphorus for Sustainable Soil Fertility

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**ABSTRACT**

Legacy phosphorus (P) in agricultural soils presents a dual challenge: in some systems, accumulation offers a substantial nutrient reserve, while in others, depletion limits crop productivity. Harnessing these contrasting realities requires context-specific management strategies that optimize P use efficiency and sustain soil fertility. In P-rich soils, legacy stocks represent a potential nutrient capital, yet their mobilization is constrained by complex soil chemical dynamics, including adsorption-desorption equilibria, mineral precipitation, and sorption mechanisms. Advances in soil chemistry reveal that not all accumulated P is equally available, necessitating innovative approaches such as pH modulation, competitive anion management, or targeted biological interventions to improve accessibility. Conversely, P-depleted soils pose critical limitations to agricultural productivity, demanding interventions to rebuild soil P capital and ensure long-term food security. Across all systems, considerable gaps remain in understanding which legacy P forms can be effectively mobilized, optimal threshold values for use, and practical strategies to integrate these insights into field management. Long-term, multi-environment research is essential to develop strategies tailored to diverse soils, climates, and cropping systems. By integrating chemical, biological, and agronomic knowledge, it is possible to leverage legacy phosphorus as a strategic resource, enhancing soil fertility sustainably while supporting resilient and productive agroecosystems worldwide.

# Domestication of intercropping soil microorganisms: Legacies from a Long-Term Field Experiment

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**ABSTRACT**

There have been numerous studies on crop phosphorus (P) uptake and utilization as well as soil P transformation in intercropping systems, yet few reports have addressed the legacy effects of soil microorganisms on P acquisition in such systems. The present study investigated the legacy effects of intercropping soil microorganisms adapted to long-term intercropping of corn and soybeans under different P application levels. A soil pot experiment was conducted using soil inoculated with training intercropping corn rhizosphere microorganisms from a continue seven-year intercropped corn field trial, and a sterilized soil treatment was included as a control. The field intercropping training trial involved three P application levels: 0, 60, and 90 kg $P_2O_5$ $ha^{-1}$ (labeled P0, P60, and P90). Corn growth, P absorption, mycorrhizal characteristics, soil bacterial, and arbuscular mycorrhizal fungi (AMF) diversity and composition under two P application rates: no P application (-P) and 40 mg P $kg^{-1}$ soil (+P) were measured. The results showed that inoculation with intercropping soil microorganisms significantly increased corn aboveground biomass and P acquisition. Under no P conditions, compared with the sterilization treatment, inoculation with intercropping soil microorganisms increased the corn aboveground biomass and P acquisition by 322-521% and 70-308%, respectively, which was significantly higher than the increase of 61-99% and 27-34% under +P conditions. Inoculation with soil microorganisms and P application levels jointly affected mycorrhizal characteristics. Compared with no P conditions, inoculation with soil microorganisms under +P conditions significantly increased the AMF colonization rate in the roots of corn by 171.06%, the hyphal length density in the rhizosphere soil by 63.44%, and the spore density by 43.28%. The colonization rate, hyphal length density, and spore density of AMF in corn inoculated with P0 treatment were significantly lower than those in P60 and P90 treatments. Phosphorus application reduced the diversity of AMF communities in the soil and enriched *Glomus*, *Claroideoglomus*, and *Acaulospora*. However, neither the P application levels nor microbial inoculation had a significant effect on soil bacterial diversity. In contrast, both treatments resulted in the enrichment of specific phyla, including *Proteobacteria*, *Actinobacteriota*, and *Chloroflexi*. In conclusion, the P application levels affected the intercropping legacy effects of P-acclimated soil microorganisms. Under the condition of P deficiency stress, intercropping soil microorganisms had a higher promoting effect on the corn growth and P absorption. Hence, appropriate reduction of P fertilizer application rate combined with intercropping could facilitate the role of soil microorganisms and promote the green and sustainable development of agriculture.

# Characterization and Dynamics of NaOH-Extractable Organic Phosphorus Species in Soils

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**ABSTRACT**

Organic phosphorus (Po) plays a critical role in soil phosphorus (P) cycling, yet the behavior and fate of specific Po species remain elusive. This study utilizes ion chromatography coupled with inductively coupled plasma mass spectrometry (IC-ICP-MS) to characterize NaOH-extractable Po species in two soil types, tracking their temporal dynamics and response to degradation. Nine distinct P peaks were identified in soil extracts, four of which remain unidentified. These species were classified into three groups: unstable species, detected only in fresh plant or algal samples; stable species, consistently present across all samples with minimal variation; and indicator species, moderately sensitive to environmental changes. Notably, the indicator species α-glycerophosphate (α-gly) and an unidentified compound (P150) exhibited significant declines over time. Along a degradation gradient, P150 concentrations decreased by 66% in highly degraded grassland soils compared to non-degraded soils, while α-gly decreased by 27%. Furthermore, IC-ICP-MS revealed a tenfold discrepancy between colorimetric and direct Po measurements, underscoring the prevalence of recalcitrant macromolecular Po in soils. These findings enhance our understanding of soil P cycling and highlight the pivotal role of small-molecular Po in maintaining soil fertility and ecosystem resilience.

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# Acidic Phosphorus-Rich Biochars Promote the Gorwth of Okra in Coastal Salt-Affected Soil: The Critical Role of Phosphorus-Transforming Bacteria

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**ABSTRACT**

Coastal salt-affected soils, as typical marginal soils, are characterized by high salinity and strong alkalinity, which easily immobilize phosphorus (P) and result in extremely low P bioavailability. Meanwhile, the global depletion of P resources has exacerbated the bottleneck in the sustainable agricultural development of these areas. Acidic phosphorus-rich biochars (PBCs), with low pH, high P-loading capacity and slow-release potential, have emerged as a potential solution. However, the mechanisms by which PBCs enhance P bioavailability and soil primary productivity through regulating rhizosphere microbial communities remain unclear. Therefore, this study used original wood chip biochar (BC1) as the control, and three types of PBCs were additionally prepared through pre-modification with $H_3PO_4$ (BC2), post-activation with $H_3PO_4$ (BC3), and co-pyrolysis of $Ca(H_2PO_4)_2$ with wood chip (BC4). A 52-day pot experiment was conducted using okra (*Abelmoschus esculentus* L.) as the test crop in coastal salt-affected soils of the Yellow River Delta, aiming to systematically evaluate the performance of PBCs in enhancing P availability and primary productivity, and to reveal the key mechanisms by which PBCs drive microbial remodeling of soil microecology and P cycling. The results showed that compared with BC1, BC2 and BC4 achieved slow and long-term P release through the combination of stable Ca-P structures, P-containing group loading, and polyphosphate precipitation. BC2 and BC4 significantly reduced the pH of coastal salt-affected soils, and increased soil available P content by 78.8%-316% 211%-431%, respectively, thereby significantly promoting okra growth and fruit yield compared with BC1. Mechanistically, PBCs restructured the rhizosphere microbial community and enriched P-transforming bacteria (e.g., *Xanthomonas*, *Pseudomonas*) with functions of organic P mineralization (*phoD*), phosphate solubilization (*gdh*), polyphosphate hydrolysis (*ppx*), and phosphate transport (*pitA*). These bacteria drove the continuous mineralization and dissolution of P in coastal salt-affected soils, thereby significantly promoting okra growth and fruit yield. This study demonstrates that PBCs significantly enhance soil P bioavailability and plant productivity in coastal salt-affected soils by reshaping the rhizosphere microbial community, which provides a new perspective for understanding the microbial regulatory mechanisms of P cycling in coastal salt-affected soils, and further offers a feasible solution with both ecological and agricultural benefits to alleviate global P resource pressure, ensure sustainable agricultural development, and promote ecological restoration in coastal regions.

**Key words:** coastal salt-affected soil remediation; acidic phosphorus-rich biochars; P availability; rhizosphere bacterial community; P-transforming functions.

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# Improved recommendations for phosphate fertilizer application to promote soil health and reduce carbon emissions

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## ABSTRACT

Traditional P fertilizer recommendation is to apply all fertilizers as basal and incorporates into soils. These ways of application result in ferric phosphate and aluminum phosphate precipitations in acid soils, and calcium phosphate precipitations in calcareous soils. These precipitations are extremely difficult to turn into available form again due to their very low solubility constants. On the other hand, acidic root exudates may not help to increase the availability of P when the roots are not fully developed in early growth stage. Incubation studies in red soil and calcareous soil indicated that P availability decreased to 38%, 44% of the amounts applied at 10 days after application (DAA) and further decreased to 30%, 26% at 180 DAA. All evidences have shown that large amounts of P fertilizer as basal lead to form the precipitates, which are subject to erosion and consequently increase risks of eutrophication in the nearby river. Plants' growth is actually related to nutrient concentration in soil solution near rhizosphere soils. Research results showed that P concentration was extremely low in real soil solution near roots, e.g., 0.5–1 mg/L. However, in hydroponic system, most plants' roots could endure N, P, K concentration as high as 210, 31, and 235 mg/L (Hogland's formula). Therefore, nutrient management that focuses on increasing nutrient concentration in soil solution near rhizosphere would be an innovative way to increase nutrient use efficiency and also improve crop yield while reduce total fertilizer applications. A series of fertilizer trials were designed and tested for major vegetables grown in the area. Type of fertilizers used, concentration of nutrients in starter solution, application method, and timing of application were step-wise evaluated and final recommendation as "Starter Solution Technology" is presented.

Application with a P starter solution (180 mg/50 mL/plant) alone after transplanting increased initial growth of tomato transplants by 36%, and application with a N starter solution (240 mg/50 mL/plant) alone boosted initial growth of tomato transplants by 105%. However, combinations of N, P and K in starter solution (4800-4200-4000 mg/L of N–P–K), could boost early growth of tomato plants by 205% at 3 weeks after transplanting (WAT) and increased 155% of early growth in chili pepper plants at 2 WAT.

To obtain higher productivity and maintain soil sustainability, same starter solution was applied at 1st and 3rd timing of topdressing, and applied of solid side-dress fertilizer at 2nd and 4th timing of application. Regardless of season or crop tested, band application of 10 ton/ha organic fertilizers as basal, plus starter solution and both liquid, solid side-dresses was always identified as the best fertilization practices in all trials. This technology increased tomato fruit yields by 27-35%, and chili pepper yields by 19-20% as compared with chemical fertilizer check. Although concentrations of N–P–K in starter solution were extremely high, however, no injures of roots were found. Same fertilization technology can be also applied in organic agriculture by replacing the starter solution to organic liquid solution.

By using this starter solution technology, total amounts of fertilizers can be reduced to 67% of N–K, 50% of P in the chemical fertilizer check treatment. Reduction of total fertilizer application results in less nutrient accumulation in soils and improves soil health. Decreases the risks of soil erosion and eutrophication, reduces of fertilizer production are all contribute to less carbon emission of soil environment.

**Keyword:** rhizosphere fertility management, starter solution, starter solution technology.

# Sustainable Phosphorus Recovery Using Modified Olive Pomace Biochar

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## ABSTRACT

In line with circular economy principles, transforming waste biomaterials into adsorbents for phosphorus recovery from wastewater offers a cost-effective approach by reducing both biowaste disposal and adsorbent production expenses. Numerous studies have shown that phosphate adsorption using waste-derived biomaterials is a more attractive and environmentally sustainable option, as it converts wastes into valuable resources. Furthermore, the use of biowaste-based adsorbents represents an innovative alternative to conventional chemical precipitation methods, which are less environmentally friendly due to their reliance on metal-based coagulants and high operational costs.

In this study, a novel biowaste that has been poorly investigated for phosphate valorisation and recovery from both synthetic and real wastewater was explored. Specifically, the potential of olive pomace–based biochar was evaluated. The olive pomace was collected from a local olive oil extraction facility, dried, and subjected to pyrolysis at 500 °C for 2 h under limited-oxygen conditions. The pyrolysis yield of the raw olive pomace biomass was 38%, which falls within the expected range for this feedstock at 500 °C. The resulting biochar was subsequently modified to enhance its surface reactivity and introduce metal sites capable of strongly binding or precipitating phosphate. The modification strategies investigated included acid treatment and magnesium impregnation applied before and after pyrolysis, and their performance was compared with that of unmodified biochar.

To evaluate the influence of pH and biochar type on phosphorus adsorption capacity, batch experiments were conducted using a synthetic phosphorus solution with a concentration of 10 mg P/L. A 0.01 M NaCl solution was added as a background electrolyte to simulate ionic strength conditions similar to wastewater. In addition, the biochars were characterized by Fourier-transform infrared spectroscopy (FTIR) to identify surface functional groups, and zeta potential measurements were performed to assess surface charge behavior across different pH values. The biochar exhibiting the highest adsorption performance was subsequently selected for further investigation. Additional adsorption experiments were conducted to examine the effects of biochar dosage, phosphorus recovery at different initial P concentrations, adsorption kinetics over time, and the influence of shaking versus non-shaking conditions.

Our next step is to test the selected biochar under real wastewater conditions and evaluate its potential use in agriculture as a fertilizer and soil amendment.

# Higher leaf phosphorus and nitrogen concentrations and greater allocation of phosphorus to lipids in Helicia and Heliciopsis than in other genera within the Proteaceae

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**ABSTRACT**

The Proteaceae is a predominantly southern hemisphere plant family that contains about 83 genera encompassing about 1600 species. Proteaceae are generally well adapted to soils poor in plant-available phosphorus (P), causing them to have generally low leaf P and nitrogen (N) concentrations, and relatively high leaf N/P ratios. One of the most recognisable adaptations to low P soils in most Proteaceae is the ability to form cluster roots, short-lived clusters of 10's to 100's of determinant rootlets per centimetre of secondary lateral root. When mature, cluster roots exude a burst of carboxylates and often phosphatases that release inorganic and organic P sorbed to soil particles and hydrolyse organic P to inorganic P, respectively. The mobilised inorganic P can then be taken up by plants. *Helicia* and *Heliciopsis* are the only genera of Proteaceae found in Asia. There are about 115 species of *Helicia*, ranging from the east coast of Australia to southern Japan and extending westward to Sri Lanka. There are about 20 species of *Helicia* in China. *Heliciopsis* contains about 14 species and is only found in south Asia, with three species found in China. We examined three species from each genus found on acid soils with low plant-available P in Yunnan and Guangxi provinces. We found cluster roots on four species, indicating that cluster roots are likely produced by most species in these genera. We found that both genera have high leaf P and N concentrations compared with most other genera of Proteaceae but have N/P ratios that are similar to genera from extremely P-poor habitats. These observations indicate that the higher leaf P concentration is likely used to increase leaf protein concentration. Upon examining one species from each genus, we found that each allocated a higher proportion of leaf P to phospholipids than to other P fractions when compared to species from severely P-impoverished environments. This difference in investment strategy presumably improves membrane function. Our results add knowledge to an understudied genus of low-P specialist plants that may be useful for forest restoration.

**Acknowledgments**

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# Phosphorus acquisition and pathogen defense: synergies versus trade-offs

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**ABSTRACT**

During their life cycle, plants encounter simultaneous biotic and abiotic stresses. A low availability of inorganic phosphorus (P) commonly limits plant growth in natural and agricultural ecosystems. Pathogen attacks pose risks to plant productivity and biodiversity, causing yield loss and ecosystem degradation. Plants evolved various strategies to cope with P limitation, which, in turn, affect their resistance to pathogens. However, a comprehensive understanding of how efficient plant P-acquisition strategies influence their pathogen resistance under P-limited conditions remains elusive. We highlight how these P-acquisition strategies can enhance or decrease pathogen resistance through multiple mechanisms. We advocate using this information to design more sustainable agricultural systems and explain species turnover in natural ecosystems, especially in the context of global change.

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# Phosphorus Status and Management Implications for Sustainable Crop Production at the Institute for Agricultural Research Farm, Ahmadu Bello University, Zaria, Northern Nigeria

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**ABSTARCT**

Phosphorus (P) is a critical yet limiting nutrient for crop production in many tropical soils due to fixation, low native availability, and inefficient fertilizer use. This study assessed the phosphorus fertility status of soils at the Institute for Agricultural Research (IAR) farm, Ahmadu Bello University, Zaria, Northern Nigeria, to generate evidence to support sustainable phosphorus stewardship and improved nutrient management. A total of forty-seven (47) disturbed soil samples were collected across the fields at 300m grid intervals at the top soil (0-30 cm) using Edelman auger and analyzed for available phosphorus alongside selected physicochemical properties. Results revealed spatial variability in soil available P, with values ranging from low (4.41 mg/kg) to an exceptional high level (73.5 mg/kg) across the farm, indicating significant heterogeneity in P availability. Observed P availability was strongly influenced by recent fertilization, soil pH, organic carbon content, and textural characteristics, highlighting the role of inherent soil properties in phosphorus dynamics. The findings suggest that blanket fertilizer recommendations may lead to inefficient P use and underscore the need for site-specific phosphorus management strategies. Adoption of soil test-based fertilizer application, integration of organic amendments, and improved placement techniques are recommended to enhance phosphorus use efficiency, reduce losses, and sustain soil fertility. This study provides locally relevant data that bridge soil science and practical nutrient management, contributing to regional efforts toward sustainable phosphorus use and resilient agricultural systems.

**Acknowledgments**

We sincerely appreciate Prof. Ado A. Yusuf, the Executive Director of the Institute for Agricultural Research (IAR), for his visionary leadership in initiating and sponsoring the Land Evaluation of the IAR Research Farm. This project would not have been possible without his unwavering support and commitment to advancing agricultural research and development.

We extend our heartfelt gratitude to the Institute for Agricultural Research (IAR) for providing the resources and enabling environment that ensured the successful execution of this project.

We are deeply indebted to the Head of the Department of Soil Science, Prof. Aisha Abdulkadir, whose guidance, mentorship, and encouragement were invaluable throughout the course of this work. Our appreciation also goes to the participating scientists for their expertise and dedication, which greatly contributed to the success of the study.

We also wish to specially acknowledge Prof. Ya'u S. L., whose mentorship profoundly shaped our perspective on spatial analysis and its integration with conventional soil survey approaches. His insights demonstrated how geospatial techniques and classical pedological methods are complementary, together providing a more robust and holistic framework for land evaluation and decision-making.

We are equally grateful to the technical staff for their diligence and tireless efforts in both the field and laboratory. Special recognition is given to the soil analysis laboratory team, whose meticulous analysis of soil samples played a critical role in achieving the objectives of this project.

Finally, we thank everyone who, in one way or another, contributed to the successful completion of this important work. Your collective efforts have not only enriched our understanding of the research farm but also laid a solid foundation for future advancements in agricultural research.

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# Biological Approach to Phosphorus Stewardship in Calcareous Soils

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**ABSTRACT**

The limited global availability of phosphorus resources has increased the need for strategies that improve phosphorus use efficiency and reduce reliance on external inputs in agricultural systems. One of the major challenges in this context is the low availability of phosphorus in calcareous soils, where long-term pedogenic processes have resulted in high total phosphorus contents that remain largely inaccessible due to strong fixation by calcium carbonate. This constraint significantly reduces fertilizer efficiency and limits crop productivity in many arid and semi-arid regions.

In this study, the potential of a biosurfactant produced by *Pseudomonas putida KT2440* was evaluated as a biological approach to enhance phosphorus availability in calcareous soil. Both incubation and greenhouse experiments were conducted using a soil with low available phosphorus. The effects of biosurfactant application were compared with commonly used chelating agents and soil amendments, including EDTA, citric acid, and humic acid, in terms of soil nutrient availability, soil chemical properties, and maize growth.

The results demonstrated that biosurfactant application significantly improved soil phosphorus availability under calcareous conditions. Soil available phosphorus increased by up to fivefold compared to control, while maize phosphorus uptake increased by approximately 40%. In greenhouse experiments, biosurfactant-treated soils consistently produced higher maize biomass and phosphorus uptake than both the control and other treatments. Although EDTA showed strong chelation capacity, its application led to marked increases in soil electrical conductivity and altered nutrient balance, raising concerns about its environmental suitability.

The observed enhancement of phosphorus availability can be explained by several interacting mechanisms associated with biosurfactant activity. These include the formation of soluble complexes with calcium ions, which reduce calcium–phosphate precipitation, and surface-active interactions at the soil–solution interface that improve soil particle wettability and facilitate the release of phosphorus from soil minerals. Importantly, these processes occurred without substantial changes in bulk soil pH or electrical conductivity, allowing efficient phosphorus mobilization while maintaining overall soil chemical stability.

Overall, the findings of this study highlight the potential of microbial biosurfactants as a practical tool for phosphorus stewardship. By mobilizing existing, non-available soil phosphorus pools, biosurfactants can enhance nutrient use efficiency, reduce dependence on synthetic amendments, and support more sustainable soil fertility management and crop production systems, particularly in calcareous soils.

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# Endophytic fungi as a biotechnological approach to increase phosphorus use efficiency

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**ABSTRACT**

Phosphorus (P) is essential for plant growth but is frequently immobilized in insoluble forms. This is particularly relevant in arid and semi-arid, carbonate-rich soils, where alkaline pH promotes Ca–P precipitation. Despite P surpluses in many agricultural soils (about 70%), more than 55% of global cropland still shows low to medium-low P use efficiency. Microbial biostimulants, including non-pathogenic endophytic fungi, may enhance P mobilization via organic acid production and P-solubilizing enzymes.

Here, six *Trichoderma* spp. strains were isolated and screened for their ability to solubilize hydroxyapatite [$Ca_5(PO_4)_3(OH)$; Hap] in vitro. Screening was performed using a modified National Botanical Research Institute's phosphate medium in which tricalcium phosphate was replaced by Hap (NBRIP-Hap). Isolates were pre-cultured on potato dextrose agar (6 d, 22 °C) and inoculated into NBRIP-Hap under shaking conditions. Culture filtrates were collected after 1, 3, and 6 days to quantify soluble P and to determine pH and electrical conductivity. Fungal biomass dry weight and mycelial P content were determined at day 6.

Based on in vitro performance, the three best strains were selected for a pot experiment under controlled growth-chamber conditions using tomato (*Solanum lycopersicum* L.) as a model plant. Pots were filled with soils contrasting in key physical and chemical properties (texture, pH, carbonate content) and spanning different P backgrounds (total and plant-available P). The experiment aimed to quantify strain-dependent effects on soil P mobilization and plant P acquisition under standardized conditions. Results will be presented as an oral communication or poster.

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# Innovative Approaches to Sustainable Nutrient Management

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**ABSTRACT**

Fertilizer has revolutionized crop production, but a lack of evidence-based fertilizer usage has resulted in negative economic and environmental ramifications, particularly for smallholder farmers. This study aimed at developing an innovative nutrient recommendation approach, Nutrient Expert (NE), for improving yields of grain crops, cash crops and vegetables, while optimizing fertilizer input through adoption of 4R (applying the right source of nutrients at the right rate, time and place) nutrient stewardship technologies. We also evaluated its large-scale performance in enhancing crop productivity and reducing environmental impacts across cropping systems. To validate the benefits of NE on both yield and environmental protection, we compared NE with current farmers' practices (FP) in over 3,000 field experiments conducted in major crop production areas of China.

Overall, the NE treatment increased grain yield by 4.6%–13.5% and profit by 6.2%–18.8% compared to FP. In addition, NE reduced fertilizer nitrogen (N) inputs by 29.0% and 14.7% relative to FP and the standard practice (ST), respectively. Across the 3,281 sites, NE improved nitrogen recovery efficiency by 4.6–13.4 percentage points over FP. On average, NE reduced reactive nitrogen losses by 36.2% and greenhouse gas (GHG) emissions by 21.5% compared to FP. Field experiments also showed that NE treatment alleviated early blight in potatoes and slowed yield reduction by 33.9%. When NE was combined with corn straw or sheep manure, particulate organic matter (POM) increased and the disease index declined. Based on NE-guided nutrient application rates, crop-specific controlled-release fertilizers were developed. Field trials demonstrated that these fertilizers increased yields by 9.2%–12.3% and improved crop quality in rice, potato, tea, citrus, and rapeseed, despite lower fertilizer inputs.

In summary, NE is a user-friendly tool with broad applicability across diverse farm types and climatic regions. It holds significant potential for improving fertilizer use efficiency and supporting food security in smallholder farming regions of China, where N fertilizer is often over-applied or used inappropriately. NE also contributes to soil health by reducing soil-borne diseases through its effects on soil POM dynamics. Moreover, NE-guided, crop-specific fertilizers enhance both yield and quality with reduced fertilizer use. This approach may be extended to help mitigate N losses and GHG emissions in other regions globally.

**Acknowledgments**

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# Controlled-release fertilizer application:Coupling with an AI-designed maize system for more grain and lower emission

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## ABSTRACT

Controlled-release fertilizer (CRF) has proven to be a highly effective strategy for driving substantial improvements in nutrient-use efficiency while minimizing environmental cost in intensive agriculture. However, CRF application alone has a limited effect on increasing crop yield and is therefore insufficient to meet the growing demand for food. Here, we used artificial intelligence (AI) to design high-yield maize production systems and develop region-specific CRF products, which were further integrated into an AI-based CRF application strategy for high-yield maize production system (ACHYS). Firstly, we developed an AI-based high-yield maize production system based on regional climatic resources, soil conditions, we optimized hybrid selection, planting density, and sowing date to improve yield potential, and close yield gaps. Second, based on the high-yield maize nitrogen requirement dynamic, we designed the controlled-release nitrogen application strategy by considering crop growth duration, pre- and post-silking nitrogen allocation, seasonal precipitation and soil fertility. The principle was that optimized controlled-release nitrogen proportion and its release duration to match the high-yield maize nitrogen demand, allowed common nitrogen to support early growth and controlled-release nitrogen to sustain post-silking nitrogen supply and grain formation. Third, we integrated controlled-release nitrogen fertilizer design with phosphorus and potassium management to develop regional specific controlled-release nitrogen formulated blended fertilizers. ACHYS built an enhanced AI- and product- driven integrated soil-crop system management approach. Over the past decade, 27 on-farm network experiments across China's major maize production regions have demonstrated that, ACHYS increased maize yield by 19.7%, improved nitrogen use efficiency by 54.4%, and significantly reduced greenhouse gas emission. Collectively, these findings prove that integrated AI-based high-yield crop system design with innovative fertilizer products can accelerate the transformation of intensive agriculture toward higher productivity and lower environmental cost.

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# Carbon-Based Functional Fertilizers: Effective Strategies for Decreasing Antibiotics and Antibiotic Resistance Genes During the Aerobic Treatment Process of Livestock Manure and Controlling Their Spread in Soil-Cucumber Systems

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## ABSTRACT

Pig manure and biogas slurry after anaerobic digestion are the reservoir of antibiotics and antibiotic resistance genes (ARGs), the application of unpretreated pig manure and biogas slurry to soil may be harmful to human health via food chain. This study explored the effects of adding biochar (Large particle sizes biochar, LPB, 5-10 mm; Small particle sizes biochar, SPB, < 0.074 mm) to pig manure aerobic composting and the cow manure biogas slurry bio-drying process as well as hydrochar addition and molecular membrane covering (MMC) on the variation patterns of antibiotics and ARGs; subsequently, the effect of low-dose (4.68 t/ha) and high-dose (18.73 t/ha) biochar-based compost products on ARGs migration within the soil-cucumber systems were investigated. **The results show that:** (1) Compared to LPB, SPB more effectively accelerated the rise in pile temperature and prolonged the high-temperature period (>50℃). SPB and LPB additions increased the antibiotic removal rate during composting from 40% to 50% and 76%, while SPB decreased the absolute abundance of ARGs and mobile genetic elements (MGEs) by 28% and 19%; (2) during cow manure biogas slurry bio-drying, the peak temperature of the pile reached 76.1–77.4°C, approaching ultra-high temperatures (>80°C) without the addition of ultra-high-temperature bacterial agents. The final moisture content decreased to 25.2%–31.5%, whilst achieving 95.4%, 98.6%, and 86.7% removal of antibiotics, ARGs, and MGEs from the biogas slurry during bio-drying, with the MMC showing enhanced efficacy over hydrochar addition. *Methanosarcina*, an anaerobic methanogenic archaea, was identified as a potential host for ARGs and MGEs exhibited the most significant direct effect on ARGs; (3) subsequently, the application of both traditional and biochar-based compost products at low-dose (4.68 t/ha) (2022) and high-dose (18.73 t/ha) (2023) levels to the same soils in different years increased soil organic matter and N, P, K content. However, the application of low-dose compost products increased the abundance of ARGs and MGEs in both soil and cucumbers. For high-dose (18.73 t/ha) compost products application, compared to pre-experimental values in soil, compost products application further suppressed the proliferation of ARGs and MGEs, with SPB-based compost products showing the most effective results, followed by LPB-based and conventional compost products. Moreover, compared to the control group without fertilizer application, high-dose compost products application decreased the abundance of ARGs and MGEs in cucumbers. Soil nutrient level is a significant factor influencing the migration of ARGs from soil to cucumbers. In summary, biochar addition and MMC were effective strategies for the high-efficiency removal of antibiotics and ARGs during pig manure composting and biogas slurry bio-drying, with subsequent application of high-dose (18.73 t/ha) compost products effectively suppressing ARGs spread from soils to cucumbers.

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# Research on Creation and Application of Microbial Inoculants for Soil Conservation in Protected Tomato Production

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## ABSTRACT

According to the Food and Agriculture Organization of the United Nations (FAO), approximately 33% of the world's agricultural soils suffer from moderate to severe degradation. Notably, soil degradation in protected agriculture occurs at a rate 5 to 10 times faster than in open-field farming, posing a significant challenge to the sustainable development of global intensive agriculture. Greenhouse tomato production, representing one of the most widely cultivated vegetable crops worldwide, is severely constrained by soil degradation induced by continuous cropping, which hinders the high-quality advancement of the industry. While microbial regulation represents a core green technology for soil health maintenance, current commercial microbial inoculants generally suffer from limitations such as low targeted efficacy and inconsistent field performance. Therefore, this study aims to develop a multifunctional microbial inoculant specifically tailored for the continuous cropping systems of greenhouse tomatoes. Utilizing native microbial resources from forest ecosystems in Northeast China as the core germplasm, we screened and rationally constructed a composite microbial consortium comprising 5 *Bacillus* strains/species and 10 *Trichoderma* strains/species. This consortium integrates three core functions: disease suppression, growth promotion, and soil amelioration. Through a two-year consecutive field experiment, we systematically evaluated the restorative effects and underlying mechanisms of this inoculant on degraded soils. The results demonstrated that the functional microorganisms, applied via drip irrigation, efficiently colonized the rhizosphere and exerted multiple synergistic regulatory effects. First, the inoculant reshaped the rhizosphere microecology, suppressed soil-borne pathogens, and drove the succession of rhizosphere microbial communities toward a healthier state. Second, it significantly enhanced soil enzyme activities and expanded nutrient pools. Compared to the control, the activities of rhizosphere acid phosphatase, urease, and sucrase increased by 3.3, 2.1, and 2.1 times, respectively. Furthermore, soil organic carbon, total nitrogen, and available phosphorus contents increased by 4.63 g/kg, 0.545 g/kg, and 128.03 mg/kg, respectively. Third, it optimized tomato root architecture, increasing root volume by 2.17 times relative to the control. Field applications confirmed that the inoculant achieved the synergistic benefits of "soil restoration, yield improvement, quality optimization, and enhanced postharvest shelf life." In addition to ameliorating degraded soils, the treatment increased the maximum single fruit weight by 150 g, elevated sugar content by 3.1%, and extended shelf life by 5 to 12 days. This green regulatory system, developed using indigenous microbial resources from China, provides an effective "Chinese solution" for maintaining soil health in protected agriculture. Furthermore, it aligns closely with the "Zero Hunger" and "Life on Land" objectives of the United Nations Sustainable Development Goals (SDGs). Moving forward, we anticipate profound cooperation with global partners to jointly promote the development and field validation of specialized inoculants for diverse climatic regions, addressing global soil degradation challenges and safeguarding sustainable agricultural development.

**Keywords:** Greenhouse tomato; Continuous cropping obstacle; Soil conservation; Microbial inoculant; Rhizosphere microecology.

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# Research Progress and application of Slow/Controlled-Release Fertilizers

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**ABSTRACT**

Fertilizers play a critical role in ensuring grain yield improvement in China while the low nutrient use efficiency of conventional chemical fertilizers has resulted in considerable resource waste and environmental pressure. As an effective and sustainable solution, controlled-release fertilizers (CRFs) can significantly improve nutrient utilization efficiency and show great potential in labor saving, fertilizer reduction, and yield enhancement. However, traditional coating materials for CRFs are mainly dependent on non-renewable petrochemical resources, featuring high cost and poor biodegradability. The utilization of agricultural wastes such as straw for bio-based coating materials remains a global challenge due to their complex chemical composition, ambiguous film-forming mechanisms, and high hydrophilicity.

To address these issues, we identified the cellulose bond-breaking sites during straw liquefaction and confirmed that bio-based polyols are the dominant liquefaction products. A chain extension film-forming technology was developed to overcome the explosive polymerization reaction, laying a solid foundation for converting straw and other bio-based resources into qualified coating materials. Furthermore, a superhydrophobic modification strategy based on magnetic nanoparticle self-assembly was proposed. A thin air layer formed at the water-coating interface prevents direct water wetting, allowing moisture to diffuse inward only in vapor form, thereby delaying nutrient release. The hydrophobicity was improved by 90.5% compared with conventional petrochemical-based coatings.

An interpenetrating network densification technology densifies the coating structure and immobilizes internal impurities, inhibiting pore formation and extending the controlled-release period. The controlled-release longevity was increased by 333% relative to unmodified bio-based coatings and by 25.3% relative to petrochemical-based coatings. To improve the low toughness and high fracture rate of bio-based coatings, a self-healing modification technology using dynamic covalent bonds was constructed. The coating fracture rate was reduced from 8.1% and 5% for unmodified bio-based and petrochemical-based coatings to only 1%, achieving stable and reliable controlled-release behavior. Notably, the degradation rate of the developed bio-based coatings is 10-12 times that of petrochemical-based coatings, with complete degradation achievable within three years.

With these results and progresses, we have realized the strategic transformation from petrochemical-based coatings to green bio-based coatings for controlled-release fertilizers and provided a Chinese model for the intelligent and green production of controlled-release fertilizers. This offers important technical support for the green development of national agriculture and food security.

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# Calibration of N, P, and K for Orange-Fleshed Sweet potato (Ipomoea batatas (L) Lam) Production in an Ultisol at Ikwo, Ebonyi State, Nigeria

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## ABSTRACT

Malnutrition, poverty and hunger are the devil of hidden hunger which has already gained its ultimate importance after setting of Millennium Development Goals (MDGs) followed by Sustainable Development Goals (SDGs). Worldwide, over 2 billion people suffer from micronutrient deficiencies such as vitamin A. Orange-fleshed Sweet potato (*Ipomoea batatas* (L) Lam) is one of the foremost vital crops since all parts are valuable for human utilization, animal feed, and industrial applications. The high nutritive value of Orange-Fleshed Sweet Potato makes it a helpful option for consumption especially among children and pregnant women in underdeveloped nations where Vitamin A deficiency is a major concern. This study was carried out on an Ultisol at Teaching and Research Farm of Faculty of Agriculture, Alex Ekwueme Federal University, Ndufu-Alike (AEFUNAI) Ikwo, Ebonyi State during the 2022 and 2023 planting seasons, to assess the growth and yield performance of Orange-fleshed Sweet potato (*Ipomoea batatas* (L) Lam) in order to determine the optimal rates of N, P and K fertilizer application and its impact on soil chemical properties at Ikwo. The treatments were Urea (N) applied at four levels namely 0, 45, 90, and 135 kg/ha; Triple Super Phosphate (TSP) applied at four levels namely 0, 15, 30, and 45kg/ha and Muriate of Potash (MOP) applied at four levels namely 0, 20, 40, and 60 kg/ha. The experiment was factorial arranged in a Randomized Complete Block Design (RCBD) with three (3) replications. Orange-fleshed Sweet potato (OFSP) data collected were vine length (cm), number of leaves, number of branches, weight of storage root/plot (kg/plot), and total storage root yield (t/ha). Soil samples were collected with a soil auger at a depth of 0 to 20cm at the end of the experiment for chemical analysis such as soil pH, organic carbon, available phosphorus, total nitrogen, exchangeable acidity, and total exchangeable bases such as $K^+$, $Ca^{2+}$, $Mg^{2+}$, and $Na^+$. All data collected were subjected to Analysis of variance (ANOVA) for factorial experiment in Randomized Complete Block Design (RCBD) using GenStat statistical package 17$^{th}$ Edition with the treatment means separated using the Fisher's Least Significant Different (FLSD) at 5% probability level and Pearson's correlation analysis was carried out between soil chemical properties values with that of growth and yield parameters of orange-fleshed sweet potato using IBM SPSS Statistics 20 package, while the optimum rates of N, P and K applications were determined following a graphical method using Microsoft Excel 2019 to obtain regression equations, which when differentiated produced x-values representing the optimum rates of applied fertilizers for orange-fleshed sweet potato production. The results obtained indicates that the application of fertilizer rate of 135 kg Urea, 45 kg TSP and 60 kg MOP produced greater improvement in soil chemical properties in both 2022 and 2023 planting seasons. Also, the growth and yield parameters of orange-fleshed sweet potato were improved significantly ($P < 0.05$) with the application of 90 kg Urea, 30 kg TSP and 40 kg MOP compared to the control in the two years of the experiment. Moreover, the application of 88.58kg and 89.92 kg N/ha produced maximum yield of 6.2t and 6.98t/ha; 32.51kg and 33.32kg P/ha produced maximum yield of 55.99t and 7.03t/ha; and 36.03kg and 42.25kg K/ha produced maximum yield of 6.07t and 7.06t/ha in 2022 and 2023 planting seasons respectively at Ikwo. Consequently, there is a positive and highly significant ($P = 0.01$) correlations between soil chemical properties and yield components of orange-fleshed sweet potato. The application rate of Urea fertilizer of 89kg/ha, TSP fertilizer of 32.5kg /ha and MOP fertilizer of 42kg/ha is highly recommended for the production of OFSP in Ikwo.

**Keywords:** Calibration, OFSP, yield, growth

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# Short-term effects of molasse-derived digestates from one- and two-stage anaerobic digestion on wheat crop and chosen soil properties

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## ABSTRACT

This study aimed to evaluate the short-term effects of molasses-derived digestates from one- and two-stage anaerobic digestion processes on a winter wheat crop and selected soil characteristics. A microcosm experiment was conducted in Central Poland under a temperate climate. Twenty plots, each measuring 1 m x 0.5 m, were established in 2023, and winter wheat was planted during the subsequent two seasons at a sowing density of 400 grains per m². The experimental design included not fertilized (NF) plots and plots fertilized with an optimized mineral fertilizer (MF), as well as plots that received one-stage (1-SD) or two-stage (2-SD) digestate. The fertilizer doses were calculated based on nitrogen (140 kg $ha^{-1}$ per year), and applied at two doses. Soils were sampled from the humus horizon using a corer just before the first fertilizer application (early spring) and immediately after harvest. The soil pH, as well as the contents of total organic carbon (TOC), total N, and the bioavailable forms of N ($NO_3^-$N and $NH_4^+$N), P, Na, K, Ca, Mg, Mn, Cu, and Zn were determined. The wheat crop characteristics included plant density and height, grain and straw mass, number of grains per ear, and mass of 1000 grains. The results revealed significant variations in wheat crop characteristics depending on the fertilization variant. The greatest differences were noted between the NF and MF, which usually represented the minimum and maximum values, respectively. Wheat at NF plots was characterized by the lowest values of all studied parameters. In contrast, MF plots represented the highest values. Plots fertilized with digestates exhibited wheat crop characteristics intermediate between NF and MF, and differences between 1-SD and 2-SD were usually low. The effects of various fertilization practices on the studied soil properties were not fully clear. An increasing tendency in pH and relatively stable levels of TOC and N were recorded in every plot. Most of the bioavailable nutrients showed increasing trends during the experimental period; however, this occurred in all plots, including NF, which is difficult to explain. Such trends were typical for P, Ca, Mg, Mn, Cu, and Zn. Conversely, the contents of $NO_3$-N and $NH_4^+$-N decreased steadily without variation depending on the fertilization variant. The application of digestates significantly increased the content of bioavailable Na and K compared to the NF and MF variants. However, there were no significant differences between the 1-SD and 2-SD plots. In summary, we confirmed the fertilization value of one- and two-stage digestates. However, the effects of their application are much lower compared to optimized mineral fertilization. Additionally, the differences between the tested types of digestate are low in terms of their effects on the wheat crop and soil properties.

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# Optimization of ethyl cellulose-coated urea for high-performance controlled release

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**ABSTRACT**

The development of controlled-release urea (CRU) using ethyl cellulose (EC) represents a significant strategy for advancing the green and sustainable development of agriculture. However, limited research on EC-coated urea preparation was reported before. This study employed EC/ethanol to develop CRU through fluidized bed technology and investigated the effects of the coating processes, material plasticization modification and surface treatment on the film structure and nitrogen release properties of CRU. The results demonstrated that the fluidizing gas temperature significantly influenced both the film structure and release performance. When the coating temperature was 50 ℃, a continuous and uniform dense film was formed, resulting in optimal controlled-release performance lasting up to 7 days. Additionally, the effects of the peristaltic pump rate and coating liquid concentration were minimal. The plasticization effect of DBS was validated through XRD analysis, which demonstrated a reduction in the crystallinity of the EC, an enhanced fracture elongation of the film, and an extended controlled-release performance to 10 days. Furthermore, surface treatment with 1 % and 2 % paraffin wax improved the water barrier properties of the film, increasing its water contact angle from 100°. Consequently, the controlled-release period of the coated urea was extended to 50 days, meeting the ISO 18644:2016 standard. This study is valuable for fertilizer production and provides a References for cellulose- coated fertilizers.

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# INTEGRATED BIOFERTILIZER AND NPK APPLICATION ENHANCES SOIL QUALITY AND PRODUCTIVITY OF ONION AND WHEAT IN SEMI-ARID ENVIRONMENTS

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**ABSTRACT**

Declining soil fertility and the limited efficiency of conventional soil amendments are critical constraints to sustainable agricultural productivity in semi-arid ecosystems. Integrated soil fertility management (ISFM) offers a viable approach for restoring soil nutrient reserves and enhancing crop performance. This study investigated the effects of different fertilizer regimes on soil physicochemical properties and the productivity of onion (*Allium cepa* L.) and wheat (*Triticum aestivum* L.) under semi-arid conditions at the Usmanu Danfodiyo University Teaching and Research Vegetable Farm. Four treatments were evaluated: chemical fertilizer (Alelawa NPK 20:10:10), biofertilizer (Bio-NPK; NANDO product), a combination of both, and an unfertilized control, arranged in a randomized complete block design (RCBD) with three replications. Baseline soil analysis revealed a sandy loam texture, slightly acidic pH, low Nitrogen, organic carbon and available phosphorus, and high bulk density. Application of Bio-NPK alone slightly reduced soil pH (from 6.80 to 6.41) and bulk density (from 1.80 to 1.73 g $cm^{-3}$), while increasing organic carbon, Nitrogen and phosphorus contents. Similar but more pronounced improvements were recorded under combined Bio-NPK and chemical fertilizer application. Fertilizer treatments had a significant effect on crop yields. Onion yield was highest under the combined Bio-NPK treatment (13.25 t $ha^{-1}$), outperforming the sole applications and control (4.60 t $ha^{-1}$). Wheat grain yield ranged from 267.9 to 797 kg $ha^{-1}$, with the combined treatment producing the highest yield (797 kg $ha^{-1}$). These results demonstrate that integrating biofertilizers with conventional NPK fertilizers substantially improves soil quality and crop productivity in semi-arid regions, offering a sustainable pathway to enhanced food security.

**Keywords:** Soil fertility, Bio-NPK, Integrated nutrient management, Onion, Wheat, Semi-arid soils

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# Rhizobial Isolate YL 14 Biofertilizer Substitutes for Urea Fertilizer and Improves Yardlong Bean Growth and Nutrient Content

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## ABSTRACT

Yardlong bean (*Vigna unguiculata* subsp. *sesquipedalis*) is a nutritionally valuable and economically important vegetable both within Thailand and internationally. However, the application of chemical fertilizers to boost its production due to high consumer demand damages the soil environment. Therefore, this study aimed to evaluate the plant growth promotion (PGP) ability of rhizobia strains from yardlong bean root nodules as biofertilizer alternatives to boost sustainable yardlong bean production. All isolates from the initial pool of 19 isolates exhibited effective nodulation, however, isolates YL 1, YL 3 and YL 14 had the highest phosphate-solubilization (103.20 ppm), potassium-solubilization (22.55 ppm), and Indole-3-Acetic Acid production (52.20 ppm). Overall, isolate YL 14 had the best PGP traits. To confirm this, a split-plot Completely Randomized Design (CRD) experiment with four replications was conducted in the lab, where the PGP ability of the three rhizobia isolates (YL 1, YL 3, and YL 14) was tested at nine dilution levels: $10^{-1}$ to $10^{-9}$. The results showed that the $10^{-2}$ dilution of YL 14 produced the highest shoot fresh and dry biomass (3.86 and 0.4 g/plant, respectively). Furthermore, results from a subsequent CRD pot experiment in the greenhouse comprising control, chemical fertilizer (Urea - 46:0:0), and YL 14 powder inoculant treatments were consistent with those obtained in the lab: YL 14 significantly enhanced plant growth, yielding the overall highest average fresh and dry weight (110.27–117.73 and 21.96–22.89 g/plant, respectively), chlorophyll content (50.19), and nitrogen concentration (2.32%). Additionally, YL 14 improved all tested parameters compared to the control ($p < 0.05$), and increased shoot and root dry weights, root fresh weight, chlorophyll and nitrogen contents compared to the urea fertilizer treatment ($p < 0.05$). Collectively, these findings highlight the potential of YL 14 biofertilizer to replace urea fertilizer in enhancing the yield and supporting sustainable yard long bean production due to its multiple PGP traits.

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# Development of carrier-based microbial inoculant and the assessment of soil application impact on Faba bean (Vicia faba) growth

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**ABSTRACT**

Faba bean (*Vicia faba*) is a niche pulse crop in Western Australia (6000 tonnes per year[1)], largely targeting markets in the Middle East. This study focused on commercial production of carrier-based inocula, considering relative cost, efficacy, ease of use, and machinery availability. There were two segments: laboratory-scale inocula production and trialing the inocula efficacy in a glasshouse. In addition to non-inoculated control (treatment 1-T1), the consortia, a mixture of rhizobia species specific to different pulses and microbes used in this study (T2), faba bean-specific rhizobia strain SRDI969 (Group F) (T3), *Bacillus megaterium* (T4), mycorrhizae (T5), and *Trichoderma sp*. (T6) to assess the impact on growth. As the initial step, microbial strains were harvested at their log phase (>$10^8$ cfu $mL^{-1}$) and stored at 4 ºC until further processing. Then, microbial strains, were coated to carrier considering moisture retention and cell viability. Sterilised Hoagland solution (0.5-strength) was prepared without nitrogen and added to the pots containing presterilized soil as a basal nutrient supplement (0.1 L $kg^{-1}$) until reaching 60% of the water holding capacity. The surface sterilised faba bean seeds (cv. Samira) were placed in soil 1 cm deep together with the prepared bacterial inocula (1 g $seed^{-1}$). The pots were arranged in a randomised complete block design in a glasshouse; throughout the study, sterilised water was added to maintain the field capacity. The plants were grown until anthesis (~40 days), and the parameters measured were chlorophyll fluorescence, dry biomass, mineral nitrogen and dehydrogenase enzyme activity in the rhizosphere soil, shoot total nitrogen content, and root nodulation and morphological characteristics. One way ANOVA (n=3) was conducted using R, after Shapiro Willis test indicated the data were normally distributed. Significantly ($P \leq 0.05$) higher chlorophyll fluorescence ($P=0.001$) was observed in mixed inoculum treatment (T2) compared with the control (T1). Shoot dry biomass was higher in the inoculated treatments (T2-T6) than in the control. Mineral nitrogen in the rhizosphere soil ($P=0.000$) was significantly higher in T3 than the other treatments. Total root length and average root diameter were lower in the control compared to the other treatments, and a similar trend was observed in dehydrogenase enzyme activity. As expected, crown nodulation was observed only in T2 and T3. These findings suggest that the produced inocula positively influenced faba bean growth and the soil health parameters.

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# Use of polyhalite as an ameliorant for sodic soils

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**ABSTRACT**

Sodic soils are widely distributed globally across semi-arid and arid regions, with agricultural productivity often limited due to structural instability caused by high concentrations of exchangeable sodium ($Na^+$). This instability is caused by clay dispersion and leads to reduced water infiltration, surface crusting, and poor seed germination. Although gypsum and other organic ameliorants are commonly used to address sodicity, the use of polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$) is of potential interest given that it is a multi-element amendment that could potentially co-supply limiting nutrients at the same time as supplying Ca to aid $Na^+$ removal. We conducted a 60-day incubation study to examine the amelioration of sodic soils from Australia using both inorganic and organic amendments, being gypsum, polyhalite, chicken manure, pig manure, and polyacrylamide (PAM). Two application rates of polyhalite were used, with polyhalite supplied at a rate in which the Ca content was equivalent to that of gypsum, and a second in which polyhalite was supplied at a rate such that the combined Ca and Mg content was equivalent to that of Ca supplied in gypsum. It was found that the application of both inorganic (gypsum and polyhalite) and organic (chicken manure, pig manure) were effective in improving structural stability, Polyhalite was equally effective as gypsum in improving structural stability, but with the added benefit of nutrient co-supply (K and Mg). Nevertheless, it was observed for all amendments that effectiveness tended to decrease somewhat over time, highlighting the need for reapplication to ensure long-term effectiveness.

**Key words:** Sodic soils, polyhalite, exchangeable sodium, aggregate stability, mean weight diameter (MWD).

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# Potassium availability but not movement from fertilizer bands is affected by the form of potassium, soil type, and co-application of phosphorus

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## ABSTRACT

The banding of potassium (K) fertilizers is becoming increasingly common and may disrupt K stratification within the soil profile. Although the movement and availability of K from these fertilizer bands are critical in determining subsequent plant uptake, much remains unclear in this regard. This study examined the movement and potential availability of K from fertilizer bands, using different K sources (sulfate of potash granules[SOP], and polyhalite granules as POLY4 ($K_2SO_4MgSO_42CaSO_4 \cdot 2H_2O$), three soils differing markedly in their properties (a calcareous Alfisol, an Ultisol, and an Oxisol, all with low levels of potentially available K) and co-application of P (monoammonium phosphate [MAP]). The diffusive gradients in thin-films (DGT) technique was used to visualize the movement of K and P into the soil from the fertilizer bands. In addition, synchrotron-based X-ray absorption near edge structure (XANES) spectroscopy was utilized for both K and P to determine changes in speciation. The results from the DGT and soil analyses showed that after incubation for two weeks, the distance that the K moved in all three soils was similar despite the three soils differing markedly in their properties (including cation exchange capacity [CEC] and clay content). Similarly, K movement away from the band did not differ markedly between the two K sources (SOP and POLY4) or with the co-application of MAP. However, it was observed that the application of K as POLY4 resulted in higher water-soluble K concentrations than SOP (by 41-130 mg K kg-1) and correspondingly lower exchangeable K (by 29-67 mg K kg-1) after incubation for two weeks, due to the competition of Ca and Mg with K for exchange sites. It was also noted that the co-application of P with POLY4 decreased water soluble K concentrations by 41-115 mg K kg-1 in the Alfisol (< 30 mm) and by 33-50 mg K kg-1 in the Oxisol (< 50 mm), but increased exchangeable K concentrations by 32-39 mg K kg-1 in the Alfisol (10-80 mm), 55-93 mg K kg-1 in the Ultisol (< 30 mm) and 123 mg K kg-1 in the Oxisol (0-10 mm). These effects were likely due to the formation of compounds, being Ca- and Mg-phosphates in the Alfisol, Fe-phosphates in the Oxisol, and Al-phosphates (e.g., taranakite) in the Ultisol. Indeed, XANES analyses for both P and K indicated the formation of taranakite-like compounds in the Ultisol following the co-application of P. The findings here suggest that deep banding of K fertilizers, including POLY4, may have the potential to overcome K stratification particularly in soils with high CEC. In addition, P co-application may slow K release in acidic soils with high concentrations of soluble Al. Further studies are warranted regarding how Ca and Mg in polyhalite will affect K movement and availability in strong K-fixing soils and in the presence of plants.

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# Diatomaceous bio-silicon as a sustainable alternative to mineral silicon fertilizers: Impacts on rice yield, soilfertility, and heavy metal dynamics

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**ABSTRACT**

Rice production faces dual challenges of insufficient plant-available silicon (Si) in soils and environmental risks from conventional Si fertilizers. While diatoms, as bioactive silicon sources, show potential for soil amelioration and yield enhancement, their dose-response relationships and mechanistic roles in paddy ecosystems remain poorly understood. This study systematically investigated the synergistic effects of diatom (DI), natural diatomaceous earth (NDE), alkali-modified DE (ADE), and commercial Si fertilizer (CF). Three levels of Si application were established: low (0.0625 g $SiO_2$ $kg^{-1}$ soil, equivalent to 122 kg $SiO_2$ $ha^{-1}$) alleviated silicon deficiency stress, medium (0.125 g $SiO_2$ $kg^{-1}$ soil, equivalent to 244 kg $SiO_2$ $ha^{-1}$) and high (0.25 g $SiO_2$ $kg^{-1}$ soil, equivalent to 488 kg $SiO_2$ $ha^{-1}$) doses were employed to investigate potential effects of silicon excess on the soil-plant systems. We quantified key soil parameters (including pH, nutrient availability) and rice agronomic traits (including tiller number, plant height, panicle weight, grain yield). We employed Partial Least Squares Path Modeling (PLS-PM) and Principal Coordinate Analysis (PCoA) to conduct multidimensional dissection of the Si source-soil-crop interaction network. Results revealed that medium-rate diatom treatment (0.125 g $kg^{-1}$ soil) significantly enhanced soil available Si, alkaline-hydrolyzable N, and available K (by 4.6%, 10.7%, and 44.0%, respectively), reduced Cd and Pb bioavailability (10.3–7.6%), and increased rice yield (41.7%) via improved nutrient assimilation (total N: +13.4%; total K: +24.6%) and optimized agronomic traits (seed-setting rate: 94.8%; harvest index: 44.9%). PCoA and PLS-PM demonstrated that diatoms remodeled soil nutrient networks through sustained Si release, mediating heavy metal detoxification and yield synergism. As the first systematic exploration of silicon cycling dynamics mediated by living diatoms in paddy soils, this study clarifies clarifies the unique benefits of silicon uptake and stress tolerance in rice compared to fossilized sources, providing practical guidance for optimizing sustainable silicon management strategies in agriculture.

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# Nanotechnology-based strategies for enhancing phosphorus and nitrogen delivery and utilization efficiency by crop species

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## ABSTRACT

Low use efficiency of conventional fertilizers creates significant environmental damage and impedes global food security, particularly given the 60-70% increase in food production needed by 2050 to support the population. Further confounding these efforts is climate change, which is forcing crop cultivation under more marginal conditions. The low efficiency of nitrogen and phosphorus use represents perhaps the most significant shortcoming of conventional agriculture, wasting tremendous resource inputs and causing significant environmental damage. We are exploring nano-enabled strategies to increase the efficiency and precision of macronutrient application. For nitrogen, efforts have focused on enhancing biological nitrogen fixation (BNF) to reduce use and increase yields. BNF relies on prokaryotic species fix N2 to NH3; these species form symbiotic relationships with legume roots. Enhancing BNF could reduce resource inputs for fertilizer production and subsequent greenhouse gas emissions. In fact, excessive use of synthetic nitrogen fertilizers likely severely limits BNF activity. We have demonstrated that nanoscale MoS2, Fe3O4, and NiO modified with sucrose, chitosan, and/or silica can enhance BNF by several mechanisms. For phosphorus, nanoscale tunable biopolymer-based strategies can control availability, including nutrient embedding in nanocellulose-based hydrogels that are modified with hydrophobic shells to tune release. Separately, different forms of nanoscale or conventional phosphorus have been blended with polymers biopolymers to control release and availability. Another project is investigating citrate-stabilized amorphous calcium phosphate nanoparticles that are doped with micronutrients as a fertilizer, as well as impacts on the rhizosphere microbiome. In all cases, phosphorus materials were used in plant-growth studies, with significant findings including up to 90% decreases in nutrient leachability/run-off, increased in planta phosphorus, biofortification of other micronutrients, and increased bioavailability of residual soil P. This work collectively demonstrates that nanotechnology-based solutions safely increase fertilizer use efficiency and crop yield, which is critical to reducing the negative environmental impacts of agriculture and for combatting global food insecurity in a changing climate.

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# Dissolution of Ca-Mg-K Based Mineral Fertilisers at the Immediate Soil Surface and Impacts on Soil Erodibility and Soil Surface Crusting

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**ABSTRACT**

A substantial proportion of the world's soils have undergone degradation, leading to increased dependence on mineral fertiliser application. Degradation increases the risk of aggregate breakdown and soil sealing under rainfall or irrigation. In productive agricultural soils, exchangeable cations are typically in the order $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$. Depending on inherent soil characteristics, deviations from this can either promote aggregation or physico-chemical dispersion. This study quantified the effect of commercially available mineral fertilizers Sulphate of Potash, Muriate of Potash, LIMEX® and three forms of Polyhalite on soil erodibility and soil crusting. Dissolution of the mineral fertilizers tested and partitioning in the surface crust and sub-surface soil matrix were also investigated. Experimental soils were obtained from the United Kingdom, France, and Brazil in order to investigate the influence of contrasting physico-chemical soil characteristics and mineralogy.

Air-dried sieved (<2.0 mm) soils were uniformly packed into 100 mm internal diameter and 50 mm deep PVC microcosms and subjected to a single intensity storm event [80 (± 5.0) mm $h^{-1}$,14 min duration]. The experiment was divided into a wet and dry phase. During the wet phase, splash detached material was collected in a 300 mm diameter concentric ring collector and post-rainfall unsaturated hydraulic conductivity ($K_{un}$) measurements made using a Minidisk infiltrometer. Each microcosm was fitted with a type MOM, 10cm long, Ø 2.5mm Rhizon Sampler and soil solution extracted via evacuation tubes. The relative proportion of Ca, Mg, K, S and Na in the soil solution, soil matrix and soil crust was determined using a Perkin Elmer 950D ICP-MS. For the dry phase, penetrative resistance of the surface crust was evaluated using an Instron Bluehill® system. This study provides invaluable insights into the effect of Ca-Mg-K based mineral fertilisers on soil erodibility and soil crusting.

**Keywords:** Ca-Mg-K based mineral fertilisers, soil erodibility, soil crusting, polyhalite

# Potassium Precipitation Efficiency at Different Dilution Ratios in Thai Sugarcane Molasses

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**ABSTRACT**

Sugarcane (*Saccharum officinarum* L.) is an economically important crop worldwide, supplying the primary feedstock for sugar production, while its by-products support a range of downstream industries. Molasses, a viscous dark-brown by-product of sugar processing, contain high levels of potassium (K). Efficient K recovery from molasses has been demonstrated using a two-step precipitation process consisting of dilution followed by the addition of calcium acetate and sulfuric acid to form syngenite (Otani et al., 2023). However, it remains unclear whether Thai molasses, derived from different cane varieties and processing conditions, exhibits similar precipitation behavior. This preliminary study used molasses from a sugarcane mill in central Thailand to evaluate the effect of dilution ratios on K precipitation efficiency and identify the dilution level that maximizes K recovery. The molasses sample was first analyzed for pH, electrical conductivity (EC), and total K content, and then diluted with $H_2O$ at ratios of 1:0.3, 1:0.4, 1:0.5, 1:0.6, 1:0.7, 1:1.0, and 1:1.25 (w/w). Each dilution was reacted with calcium acetate and sulfuric acid in triplicate. Precipitates were collected, oven-dried, and weighed, and their total K contents were determined. The remaining supernatant was analyzed for pH, EC, and total K.

Preliminary analysis of the Thai molasses sample showed that it was slightly acidic ($pH_{1:2}$ water = 4.75) and had a high $EC_{1:2}$ water of 15.28 mS $cm^{-1}$, reflecting its concentrated ionic composition. The molasses was also rich in K, containing 30.29 g $kg^{-1}$, confirming its suitability as a K-rich feedstock for precipitation-based recovery. Dilution ratio had a significant effect on both the quantity and K concentration of the precipitates ($p < 0.01$). The highest precipitate yields were obtained at dilution ratios of 1:0.40 and 1:0.60. Total K concentration in the precipitates also varied significantly, ranging from 30.27 to 51.44 g $kg^{-1}$, with the highest concentration observed at the 1:0.70 dilution, followed by the 1:0.40 dilution. However, when considering the actual amount of K recovered, the 1:0.40 dilution ratio was the most effective, achieving the highest K recovery of 51.83%. The supernatant from this treatment had a pH of 2.84, an EC of 8.27 mS $cm^{-1}$, and a residual total K concentration of 12.73 g $kg^{-1}$, indicating efficient removal of K from solution. Overall, the results indicate that an intermediate dilution ratio of 1:0.40 provides the most efficient conditions for K recovery from Thai sugarcane molasses. However, further investigation is needed using molasses samples sourced from different regions of Thailand, as well as different calcium salts, to confirm the robustness and broader applicability of the process.

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# Nitrogen Release and Greenhouse Gas Emission From soils Treated with Biodegradable Polymer-Coated Urea Fertilizer

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**ABSTRACT**

Poly butylene adipate-co-terephthalate (PBAT) is an aliphatic–aromatic copolyester-based biodegradable plastic derived from petroleum resources. Conventional non-biodegradable polymers used in controlled-release fertilizers (CRFs) effectively regulate nitrogen release but persist in soil for extended periods, leading to microplastic contamination. In this study, the effects of PBAT-coated urea and polyethylene (PE)-coated urea on soil available nitrogen concentrations ($NH_4^+$ and $NO_3^-$) and greenhouse gas ($CO_2$, $CH_4$, and $N_2O$) emissions were compared with those of uncoated urea and a non-fertilized control. Each treatment was applied at a rate of 0.4 g of fertilizer per 200 g of soil and incubated at 25℃ for one month under dark conditions. To evaluate the effects under upland and paddy conditions, two moisture levels (60% water-holding capacity (WHC) and continuous flooding) were maintained. Under 60% WHC, $NH4^+$ concentrations showed no significant differences among treatments at the initial stage but were highest in the urea treatment at the intermediate stage. Under flooded conditions, $NH_4^+$concentrations were initially significantly higher in the urea treatment due to rapid hydrolysis of urea, while PE- and PBAT-coated urea treatments maintained higher levels during the intermediate stage as a result of delayed nitrogen release. Although both coated fertilizers showed prolonged $NH_4^+$ retention in the late-stage, PBAT-coated urea showed earlier nitrogen release compared with PE-coated urea, which might be attributed to faster biodegradation of the PBAT relative to PE. Under 60% WHC, $NO_3^-$concentrations increased in a sigmoidal pattern due to nitrification whereas in flooded conditions, $NO_3^-$ accumulation was 91% lower. $CO_2$ emissions were greatest in the PBAT and PE coated urea treatment under 60 % WHC and flooded conditions, respectively, suggesting that microbial activity associated with degradation of the polymer coatings under aerobic conditions. $CH_4$ emissions were highest in the PE-coated urea under 60% WHC and in the urea treatment under flooded conditions. Under flooded conditions, urea promoted $CH_4$ emissions because nitrogen sources could enhance methanogenesis. Under 60% WHC, $N_2O$ emissions were elevated because aerobic conditions promoted active nitrification compared to flooded conditions. In flooded conditions $N_2O$ emission was highest in the urea treatment due to rapid urea hydrolysis enhancing denitrification. Overall, PBAT-coated urea retarded nitrogen release and reduced greenhouse gas emissions compared with PE-coated and uncoated urea fertilizers showing the potential of PBAT-coated urea as a sustainable alternative to reduce microplastic pollution and mitigate environmental impacts in agricultural soils.

**Acknowledgments**

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# Chemical Gradients in the Fertosphere: Rethinking Fertiliser–Soil Interactions

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**ABSTRACT**

Fertilisers underpin modern food production, contributing 40–60% of global crop yields. However, average nutrient use efficiency (NUE) remains low leading to economic inefficiency, depletion of finite resources, and pollution from nutrient runoff and greenhouse gas emissions. The cost and geopolitical concentration of resources, heighten the urgency of improving efficiency. Improving NUE requires rethinking how soil-fertiliser interactions are studied. Traditional approaches often overlook the steep chemical gradients that develop in the immediate zone of soil surrounding fertiliser granules (i.e. the fertosphere) where nutrient concentrations, pH, chemical reaction and speciation vary dramatically over millimetres. Understanding these gradients is crucial for designing fertiliser formulations that maximise plant uptake and minimise losses to the environment. Classic studies identified distinct reaction zones, from near-granule precipitation to outer adsorption zones, but limitations in analytical methods forced researchers to use indirect, ex situ chemical extractions that mask these dynamics. Recent advances now enable in situ and spatially resolved analyses, marking a paradigm shift. Techniques such as Diffusive Gradients in Thin Films (DGT) in conjunction with elemental mapping techniques allow mapping availability in the fertosphere in 2D. Synchrotron-based X-ray Absorption Spectroscopy (XAS) allows in situ solid phase speciation and planar optode imaging can visualise changes in pH in the fertosphere. Integrating these tools enables a mechanistic understanding of how soil and fertiliser properties interact, informing the “4R” stewardship principles: right source, rate, place, and time. This new analytical framework can guide the formulation of fertilisers with tailored dissolution behaviour, pH control, and nutrient compatibility. For instance, mapping of ammonium phosphate fertilisers shows that local acidification can drive calcium phosphate precipitation, limiting P availability in calcareous soils. At the same time, co-application of P and K fertilisers in acidic soils can lead to the formation of insoluble K, P and Al compounds. Hence, a paradigm shift is essential: fertiliser science must move from bulk to gradient-resolved approaches. This is especially urgent given the rise of recycled nutrient fertilisers derived from waste streams, which are central to circular economy initiatives. These recycled products often contain diverse chemical species with variable solubility and efficacy. Mechanistic understanding of fertosphere processes will ensure these innovations genuinely improve NUE and sustainability rather than being driven solely by waste-sector economics.

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# Pure Water-Based Nano Pesticide-Fertilizer Co-delivery for Soil-Friendly Crop Nutrition and Protection

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## ABSTRACT

Improving fertilizer use efficiency while reducing pesticide loads, soil contamination and labour demand is a key challenge for sustainable agriculture. Water-fertilizer integrated systems that simultaneously co-deliver fertilizers and pesticides and exploit pesticide-fertilizer synergism is an effective way to save labour and improve resource use efficiency. However, most hydrophobic pesticides are incompatible with aqueous fertilizers and therefore rely on organic co-solvents and heavy surfactant use when combined with fertigation, increasing costs, complicating operation and threatening soil biota and groundwater. This work presents a pure water-based nano pesticide-fertilizer co-delivery system (WNPFS) that couples crop protection with micronutrient supply in a single input, enabling simultaneous pesticide-fertilizer application to reduce labour operations and overall agrochemical input costs.

Formulation parameters are optimised to maximise micronutrient loading, colloidal stability and robustness. Physicochemical characterisation (size, morphology, zeta potential, loading efficiency) confirms well-defined, stable nanostructure. Using rice as a model crop, foliar and root applications of WNPFS are compared with commercial formulations and rigid nanocarriers for leaf retention, root uptake, translocation, pest control and plant growth. Rare-earth labelling plus multi-scale imaging and ICP-MS tracking quantify transport across the rhizosphere-root interface, leaf barriers and within tissues, linking formulation design to nutrient use efficiency and soil exposure.

Transcriptomic and metabolomic analyses identify plant pathways involved in nutrient assimilation, stress mitigation, xenobiotic detoxification and root exudation under WNPFS versus conventional inputs, providing mechanistic insight into pesticide–nutrient synergism and potential feedbacks on rhizosphere processes relevant to soil health. Overall, WNPFS defines a nano-enabled agrichemical that unifies crop protection and micronutrient delivery in a solvent-free, water-compatible, soil-friendly form, reducing reliance on solvent-based formulations that can disturb soil biota and structure, and providing a labour-saving, cost-efficient and scalable route to fertilizers that support input reduction, soil health and sustainable agricultural intensification.

***Keywords:*** Water-based nano fertilizer; Pesticide-fertilizer co-delivery; Micronutrient use efficiency; Water-fertilizer integrated systems

# MOF-303 Reinforced Bio-based Coatings for Precision Nitrogen Release in Agriculture

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**ABSTRACT**

Bio-based coated controlled-release fertilizers (CRFs) represent a sustainable alternative to petrochemical-based coatings; however, their application is often limited by loose pore structures that lead to imprecise nutrient release and reduced longevity. This study addresses these challenges by developing a novel biocomposite coating that integrates Metal-Organic Framework-303 (MOF-303) into a castor oil-based polyurethane matrix.

MOF-303 was synthesized and successfully grafted onto the bio-based coating via self-assembly, as confirmed by FTIR, XPS, SEM, and TEM characterizations. The incorporation of MOF-303 significantly improved the coating's surface morphology, transforming rough, irregular surfaces into smoother, hierarchically porous architectures with enhanced hydrophobicity.

Key findings demonstrate that MOF-303 acts as a regulator of pore structure. While low concentrations (0.5%) acted as pore-opening agents, optimized concentrations (1.0% and 1.5%) effectively reduced porosity and extended the nitrogen release period. Specifically, the release duration increased from 63 days for the unmodified coating (BCF) to 105 days for the 1.5% MOF-modified coating (MBCF3). Kinetic modeling revealed that the release mechanism shifted from non-Fickian diffusion to Case-II transport, indicating precise control over nutrient delivery.

In pot experiments with spinach (Spinacia oleracea L.), the MOF-modified fertilizers significantly enhanced agronomic performance. Compared to urea treatments, the modified CRF increased spinach yield by 37.51% and chlorophyll content by 20.4%, while reducing nitrate accumulation by 40%. Furthermore, the modified fertilizer maintained high yields even with a 20% reduction in application rate, demonstrating significant potential for improving nitrogen use efficiency (NUE) and reducing agricultural non-point source pollution. This work provides new insights into constructing pore-oriented biocomposite coatings for sustainable and precise agriculture.

**Acknowledgment**

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# Influence of a tailored composite amendment on soil health and wheat productivity in reclaimed tidal land

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**ABSTRACT**

The recent increase in climate change and grain price volatility has highlighted the importance of food security. However, due to various factors such as urbanization and limited land area, the food self-sufficiency rate in the Republic of Korea has been continuously declining. To address this issue, reclaimed lands have been developed along the west coast to secure arable land, with the Saemangeum Reclamation Project, the largest of its kind, designating one-third of its total area as an agro-bio zone. However, the reclaimed soils are unsuitable for upland crop cultivation compared to general agricultural soils due to high pH, high salinity, and low nutrient contents. This study was conducted to characterize the Saemangeum reclaimed soils and to develop a composite soil amendment using various soil materials, evaluating its effects on soil improvement and crop productivity through the cultivation of *Triticum aestivum* L. 'Saekuemgang'. Surface soils were collected and analyzed from Zones 1, 2, 4, 5, and 6 of the Saemangeum agro-bio area, and the field experiment was conducted at the test field of the National Institute of Crop Science located in Zone 5. The developed composite soil amendment consisted of cocopeat, black peat, biochar, zeolite, hydrogel, and byproduct gypsum. Application rates were set at 11, 21, and 42 bags per 50 L (50, 100, and 200%), respectively. Chemical fertilizers of $N–P_2O_5–K_2O$ were applied at rates of 8.9, 12.0, and 3.6 kg $10a^{-1}$ for all treatments including the control. Based on the agro-bio zone soil analyses, all soils were classified as non-saline normal arable soils. However, the soil fertility levels were substantially lower compared to the national average of upland soils. The field experiment results indicated that the application of the composite soil amendment significantly improved soil properties and fertility compared to the control, which consequently enhanced wheat yield across all treatment levels. Further long-term application trials and studies on various food crops are required, which are expected to contribute to strengthening national food security through the improvement of food self-sufficiency.

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# Microwave-assisted Synthesis of Multi-metal MOFs as Controlled-released Fertilizers

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**ABSTRACT**

Metal-organic frameworks (MOFs) have gained considerable attention as promising candidates for controlled-release fertilizers (CRFs) due to their tunable structures and high porosity. However, the widespread application of MOFs in CRFs has been hindered by the limitations of conventional hydrothermal synthesis methods, which are time-consuming (requiring up to 24 hours for reaction) and energy-intensive. Additionally, these traditional approaches often limit the selection of metallic elements to iron (Fe), restricting the diversity of available CRFs. To overcome these constraints, we present a microwave-assisted approach for rapid synthesis of multi-metal MOF-enabled CRFs. Through a systematic analysis of reaction parameters, we identified several key factors that govern the formation of Fe-MOFs and their nutrient release kinetics. The modulator dosage (urea-to-phosphate ratio) was found to be the most influential factor, with an optimal range of 0.5–1, followed by reaction temperature (120–160°C), reaction time (1.25–2.5 hours) and microwave power (600–800 W). The microwave-assisted process was significantly faster (8–16 times) compared to traditional hydrothermal methods, enabling synthesis within hours rather than a day. Moreover, the incorporation of additional metals, such as zinc (Zn), calcium (Ca), or a Zn/Ca mixture, altered the coordination environment of Fe-MOFs while maintaining Fe-centered coordination as the dominant structure. Characterization techniques, including PXRD and XPS, along with stability constants of coordination (Ig $K_n$) and hard and soft acid-base (HSAB) theory, confirmed these structural changes. Among the various formulations, the Zn/Ca mixture (MW12) exhibited the most significant alterations in pore structure and morphology. Multi-metal MOFs showed enhanced nutrient release rates, with a 31.0% increase in release and an 18.3% improvement in space-time yield compared to single-metal Fe-MOFs, indicating their potential for large-scale production. Specifically, MW12 demonstrated the fastest nutrient release (~9.9% over 30 days), following the diffusion-erosion kinetics. Pot trials further demonstrated substantial agronomic benefits, including a 13.8% increase in pak choi biomass and a 25.8% increase in rice seedling biomass, particularly with MW12. In summary, these findings suggest that the microwave-assisted method offers a rapid route to advanced, multi-metal MOF-based CRFs with tailored nutrient-delivery profiles.

**Acknowledgments**

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# Effects of polyhalite placement on wheat seedling establishment using X-ray Computed Tomography

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**ABSTRACT**

Polyhalite is a naturally occurring mineral containing potassium, calcium, sulphur and magnesium. It is crushed and granulated to create the slow-release, low-carbon, multi-nutrient fertilizer called POLY4, produced and marketed by Anglo American plc.

Crop roots are intrinsically sensing and seeking organs, searching the soil for water and nutrients to support growth. Despite germination and early growth stages being critical to crop yield, there is little information regarding how the application method of POLY4 affects crop rooting and establishment.

A pot experiment was used to investigate how the location of POLY4 influences the development or seedling root architecture, as well as the mobility and uptake of nutrients delivered by POLY4. Wheat seedlings were grown in columns containing POLY4 in different locations, representing different fertilizer application methods. X-ray Computed Tomography was used to quantify root development throughout germination and early establishment over 16 days. Additionally, inductively coupled plasma mass spectrometry (ICP-MS) was be used to investigate nutrient mobility in soil and uptake into plant tissues. The results of the study are important to inform effective application practices of POLY4 to the seedbed.

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# Synthesis of N-Zn Composite Synthetic Controlled Release Fertilizers

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**ABSTRACT**

Soil fertility management is greatly improved when nutrients are supplied in alignment with the physiological demands of crops, and controlled-release fertilizers (CRFs) provide an effective approach for enhancing nutrient-use efficiency while minimizing environmental losses. In the present study, composite N–Zn fertilizers were developed using a polymer-based carrier engineered to regulate the release of urea and zinc oxide (ZnO). The primary objective was to synthesize, characterize, and evaluate N–Zn composites capable of sustained nutrient delivery through polymeric encapsulation, controlled swelling, and optimized nutrient loading. The composites were prepared via polymerization of partially neutralized monomers in a 1:3 ratio, incorporating a cross-linker, filler, and initiator, with ZnO introduced at varying levels (3%, 4%, and 5%) during synthesis. Nutrient loading was achieved by swelling the resulting superabsorbent polymer in aqueous urea solutions, yielding nitrogen contents ranging from 12.47% to 21.12% and zinc concentrations of 72.09 ppm to 90.86 ppm. Swelling behavior followed the order 5% N–Zn > 4% N–Zn > 3% N–Zn, demonstrating the influence of ZnO content on water absorption and release dynamics. FTIR analysis confirmed characteristic Si–O–Si and Si–O–Al vibrations of the bentonite framework, along with O–H, H–O–H, and C–H/N–H bands indicative of hydration and nutrient interaction, while Zn–O absorptions verified ZnO incorporation. Overall, the developed N–Zn composites exhibit strong potential as controlled-release fertilizers for improving nutrient retention and advancing soil fertility management.

**Keywords:** Controlled-release fertilizer, Polymerization, Enhanced N-Zn availability, Characterization, Soil fertility.

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# Potassium fertilisers in contrasting soils: solubility, speciation and potential plant availability of alternative and conventional formulations

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## ABSTRACT

As global agricultural production increasingly relies on fertilisers, understanding the interaction between fertiliser formulations and soils is crucial for enhancing nutrient efficiency. When fertiliser is placed in soil, several reactions occur, often forming a high salt zone around the granules that affects nutrient diffusion and availability. These reactions are well studied for N- and P-containing formulations but vastly under-reported for conventional (e.g. KCl, $K_2SO_4$) and alternative potassium (K) sources (e.g., polyhalite - $K_2SO_4MgSO_42CaSO_4 \cdot 2H_2O$). To address this, we investigated nutrient release and reaction products of conventional and alternative K fertilisers in four contrasting soils. Polyhalite (as POLY4® a granulated polyhalite product of Anglo American plc. (www.poly4.com)) and sulphate of potash (SOP) fertilisers were incubated in an Aridisol, Oxisol, Alfisol, and Vertisol for 3 to 56 days. The granules were enclosed in a nylon mesh (<45 µm) attached to a 3D-printed support to position the granules in the centre of a vial filled with ~100 g of each soil at 80% water holding capacity. Unfertilised soils were incubated to account for background nutrients. At the end of each incubation period, the fertiliser-containing mesh was removed, and the remaining soil was dried, homogenised and analysed. A three-step sequential extraction then assessed various soil K pools: K directly available to plants from the soil solution (water extraction), readily exchangeable and plant-available K (ammonium acetate extraction) and, non-exchangeable K that may become slowly available for plant uptake (sodium tetraphenyl boron [TPB] extraction). Selected soil samples (14- and 56-d incubations) were also analysed for K and S solid-phase chemical speciation using synchrotron-based XANES analysis. Overall, most K released from both fertilisers was present in the readily available K pools (water and acetate extracts), with <10% recovered from the less plant-available pool (TPB extract). This distribution remained relatively consistent for the duration of the experiment (56 d) across all soil types. For all soils, 100% of the K and Mg applied as polyhalite was recovered in the soil, but <50% of the polyhalite S and <20% of the polyhalite Ca were recovered. Soil type influenced the release of these nutrients from polyhalite, where the alkaline Ca-rich soil had the least dissolution of fertiliser nutrients. This may be in part due to the common-ion effect, where the high concentration of $Ca^{2+}$ ions already present in the soil may limit the dissolution of granules and/or even lead to reprecipitation of Ca. Potassium XANES analysis suggests that differences in soil K speciation are more related to soil type than fertiliser source, where K is mostly associated with clays, iron oxide or to a lesser degree, organic matter. In soils dominated by 1:1 clays, iron oxides play an important role in K speciation.

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# Exudate pulses throughout the entire growth period trigger the increase in maize phosphorus use efficiency by modifying soil keystone microbial taxa

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**ABSTRACT**

Exudates are the medium through which plants adapt to complex soil environments, however, the mechanisms of how different types of root exudates increase maize yield and phosphorus (P) use efficiency (PUE) throughout the entire growth period remains unknown. In this study, we designed an experiment to examine the effects of continuous addition of exudate substances on maize growth and P uptake over the entire growth period. The addition of succinic acid, luteolin, and inositol significantly increased maize biomass, particularly root biomass. Specifically, the treatment with added succinic acid increased maize yield by 11.6% and PUE by 8%. Additionally, we found that different exudate substances significantly altered the soil bacterial and fungal communities, thereby increasing soil P bioavailability. The microbial co-occurrence networks revealed that Actinobacteriota and Proteobacteria keystone ASVs, enriched by the addition of succinic acid, luteolin, and inositol, were significantly associated with maize P uptake. Furthermore, at the V12 stage (Twelve leaves unfolded), the addition of exudate substances significantly increased alkaline phosphatase activity, and at the R6 stage (Maturity), soil available P content was significantly elevated, enhancing soil P bioavailability. These findings provide evidence for future exploration of the interaction mechanisms between plants and soil microbes and optimizing nutrient management strategies in farmland.The extension limit is 3000 characters with spaces in total, this including Acknowledgments and References if any.

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# Unravelling the dissolution pathways and transformation of polyhalite fertilisers in contrasting soils through multi-scale imaging and elemental analysis

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## ABSTRACT

Potassium (K) fertilisers are necessary for sustaining crop productivity, yet their global manufacturing and supply chains remain geographically concentrated, raising concerns over price volatility, supply security, and environmental impact. Among emerging alternatives, polyhalite ($K_2SO_4.MgSO_4.2CaSO_4.2H_2O$) has attracted growing attention as a natural multi-nutrient mineral source ofK, Mg, Ca, and S. Despite its increasing worldwide commercial use, its dissolution mechanisms in soil environments remain poorly characterised, limiting our capacity to predict nutrient release kinetics and agronomic efficiency. This study investigated the temporal dissolution behaviour of polyhalite formulations - commercial granules (POLY4®, a granulated polyhalite product of Anglo American plc. (www.poly4.com)); polyhalite chips - compared with sulphate of potash (SOP) in four contrasting Australian soils (Calcarosol, Ferrosol, Kandosol, Vertosol). A novel, custom-designed 3D-printed incubation system was developed to trace granule solubilisation over 56 days under controlled moisture conditions. Residual fertilisers were recovered, weighed, and analysed using µCT, X-ray diffraction (XRD), SEM-EDS, and ICP-OES to visualise internal porosity, mineral transformations, nutrient distributions and release patterns. SOP dissolved completely within three days, whereas polyhalite-based fertilisers exhibited slower, incongruent dissolution. POLY4® released nearly all K and Mg within 56 days, but only ~50 % of S and <30 % of Ca, leaving behind material composed predominantly of gypsum ($CaSO_4.2H_2O$). The dissolution of the fertilisers was remarkably consistent across soil types, indicating that fertiliser formulation, rather than soil properties, governed the solubilisation behaviour. µCT and SEM imagery revealed that POLY4®'s high internal porosity facilitated a dual-phase dissolution pattern (rapid initial release followed by slower depletion), while the denser polyhalite chips dissolved gradually through a "weathering-front" mechanism from the chip surface inward. These findings elucidate how the physical structure and mineralogy of polyhalite fertilisers dictate nutrient release profiles. The incomplete short-term dissolution should not be interpreted as inefficiency: the gypsum-rich residues possess residual agronomic value through the slow release of Ca and S and potential mitigation of nutrient deficiencies and soil constraints. Overall, polyhalite fertilisers provide a sustained-release K source, representing a valuable component in integrated nutrient management strategies. The study underscores the need to tailor fertiliser formulation and particle architecture to match crop nutrient demand and soil conditions. It also highlights the relevance of advanced imaging tools (µCT, SEM-EDS) for resolving micro-scale processes governing nutrient release from the granules and their availability within the fertosphere.

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# A Co-granulated Urea and Sulphur Fertilizer Reduces Soil $N_2O$ Emissions while Increasing Crop Yields

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## ABSTRACT

Sulphur (S) and nitrogen (N) fertilizer input increased in Canada and across the world, especially in canola-wheat cropping systems across Western Canada, the nation's central region for crop production. However, sulphate-S is susceptible to leaching, and urea can elevate nitrous oxide ($N_2O$) emissions, a potent greenhouse gas (GHG). Combining urea and S via the micronized elemental S technology (MST®), the co-granulated fertilizer products (e.g., UreaMST) were developed to improve season-long N-S availability, their use efficiencies, and reduce $N_2O$ emissions. It remains unclear whether urease inhibitors (UIs), weakening urease activity and potentially reducing $N_2O$ emissions, can impact $N_2O$ emissions when coated with UreaMST. In addition, concerns are rising about the differential influence of fertilizer placements on crop yields and $N_2O$ emissions for these fertilizers. A three-year field experiment was established in central Alberta, Canada, following a canola–canola–wheat rotation, and arranged in a randomized complete block design (RCBD) with four blocks and eight treatments (T1: no-N control, T2: no-S control, T3: side-band urea, T4: broadcast urea, T5: side-band UreaMST, T6: broadcast UreaMST, T7: broadcast urea + UI, T8: broadcast UreaMST + UI). Treatment effects on crop yields and growing-season cumulative $N_2O$ emissions were analyzed using linear mixed-effects models with year, treatment, and their interaction as fixed effects, and block and plot as random effects. Factorial effects were tested by two-way mixed-model ANOVA within the complete treatment subset: for no-UI treatments T3–T6, fertilizer (urea vs UreaMST) × placement (side-band vs broadcast); and for broadcast treatments T4/T6/T7/T8, fertilizer × UI (with or without). Controls (T1 and T2) were compared with N-S balanced fertilized treatments T3–T8 using Dunnett-adjusted contrasts ($\alpha = 0.05$). The result showed that crop yields varied strongly by year and showed significant treatment effects, with a significant year × treatment interaction: All N-containing treatments (T3-T8) significantly increased wheat yield (2025) relative to T1, and T3 and T8 significantly increased canola yield (2023) relative to T2. Within the no-UI subset (T3–T6), fertilizer effects were year-dependent (Year × fertilizer significant), while placement effects were not consistently significant across years. In the broadcast subset (T4/T6/T7/T8), UI treatments increased crop yields. The treatment and year × treatment effects on growing-season cumulative $N_2O$ emissions were significant and dominated by year effects with fertilizer and placement effects not consistent across years. In the broadcast subset, UI effects on $N_2O$ were detected ($p = 0.03$). Overall, UreaMST + UI showed 2.1% (canola) and 11.0% (wheat) higher yield than urea under broadcast, while the mean cumulative $N_2O$ emissions was 36.6% lower, indicating that the UreaMST + UI formulation is potentially a promising fertilizer strategy that mitigates $N_2O$ emissions and benefits crop yields in Alberta croplands despite varying impacts by year.

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# Comparison Evaluation of Nitrogen and Sulfur Release from Sulfur- and Polymer-Coated Controlled-Release Fertilizers

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**ABSTRACT**

Urea is widely used as a nitrogen (N) fertilizer to improve crop yields worldwide; however, sustainable N management remains a major challenge due to its loss by volatilization, leaching, surface runoff, and denitrification. To improve N use efficiency (NUE), polymer-coated fertilizers are commonly used as controlled-release fertilizers (CRF), because they release nutrients gradually in accordance with plant demand. However, concerns regarding microplastic pollution have increased interest in sulfur-coated urea (SCU), which is expected to decompose completely in soil environments. This study investigated the stability of the coating and examined the controlled-release performance of the coated urea fertilizers. In this study, we compared the N and S release pattern of six fertilizers: (1) S-Coated Urea Fertilizer 90 days (SCU-90; N 34%), (2) S-Coated Urea Fertilizer 100 days (SCU-100; N 36%), (3) S-Coated Urea Fertilizer 80-90 days (SCU-80-90; N 34.5%), (4) S-Coated Urea Fertilizer 80 days (SCU-80; N 36%), (5) Bulk Blend Fertilizer (BB; N 13%), and (6) Polyolefin-Coated Urea Fertilizer (POCU; N 42%). A leaching test was conducted in distilled water at 30 °C for 1, 2, and 7 days. In addition, to understand the controlled release mechanism of the fertilizers in a soil (Inceptisol), triplicates of each treatment were applied at an equivalent rate of 70 kg N $10a^{-1}$ and incubated for 15 weeks in a pot at 30 °C, and the water level was kept 2 cm above the surface of the soil, simulating paddy environments. $NH_4$-N was measured using a $CaCl_2$ extraction solution, and total S was extracted using a $KH_2PO_4$ extraction solution and measured with ICP-OES. Leaching tests revealed the contrasting patterns: SCU-80, SCU-80-90, and SCU-90 showed rapid initial mass loss (74.1%, 65.3%, 40.9%, respectively), whereas POCU lost only 4.2% of its weight by Day 7. Soil incubation study also showed that POCU exhibited the most sustained release of $NH_4$-N, followed by SCU-100 and SCU-90, while SCU-80 and SCU-80-90 showed the least controlled release of N. Sulfur release showed similar results with SCU-80-90> SCU-80> SCU-90> SCU-100 in soil as well as soil solution. Notably, scanning electron microscopy (SEM) analysis after the leaching test showed that the coating surface of SCU-80 and SCU 80-90 became fragile compared to other fertilizers, suggesting that lower structural integrity led to rapid nutrient release. These results demonstrate that the coating efficiency and controlled release of POCU is much higher than those of the other fertilizers, as the coating was not degraded easily. This also suggests that the coating efficiency has a strong correlation with the release pattern of the nutrients of the coated fertilizers.

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# Field evaluation of dual-inhibitor urea in baby spinach on clay soil: implications for $NH_3$ and $N_2O$ mitigation in high-input horticulture

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**ABSTRACT**

Intensive leafy-vegetable production systems often rely on split nitrogen (N) applications and frequent irrigation, creating conditions that can accelerate reactive N losses to the environment. These losses reduce fertiliser N use efficiency and contribute to air-quality impacts ($NH_3$) and climate change ($N_2O$). We conducted an on-farm field trial in irrigated baby spinach (*Spinacia oleracea* L.) on a clay soil in Victoria, Australia, to evaluate urea fertiliser with dual inhibitors (urease and nitrification inhibitors) compared with conventional urea under commercial raised-bed management.

Two large plots (60 × 20 m) were established to accommodate open-path Fourier transform infrared (FTIR) measurements, with open-dynamic chamber systems positioned within plots for complementary high-resolution flux quantification. Nitrogen was top-dressed as a split application (60 kg N $ha^{-1}$ followed by 30 kg N $ha^{-1}$). Ammonia ($NH_3$) and nitrous oxide ($N_2O$) fluxes were quantified using (i) open-dynamic chamber measurements coupled to a Picarro G2509, with intensive sampling daily for five days after each fertiliser application and tapered sampling thereafter, and (ii) continuous open-path FTIR monitoring across the 6-week production period. Soil mineral N ($NH_4^+$, $NO_3^-$) was measured on the same schedule as chamber fluxes, and crop yield was assessed at harvest.

Treatment effects were evaluated for emission dynamics (peak timing and magnitude), cumulative $NH_3$ and $N_2O$ losses, and soil mineral N transformations, and interpreted in the context of productivity outcomes. This study provides a field-scale, measurement evaluation of dual-inhibitor urea in an irrigated leafy-greens system, with findings intended to inform fertiliser product development and mitigation strategies for reactive N losses in high-input horticulture.

**Acknowledgments**

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# Improving Nitrogen Use Efficiency: Novel Enhanced Efficiency Urea Fertilisers.

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**ABSTRACT**

With the increase in world population and decrease in the arable land available, emphasis has been drawn to more effective fertiliser use, to reduce losses and improve outputs. When fertiliser is applied to the soil, it is not all stored and taken up by plants, but some is lost to the environment[1]. Using urea as an example it is estimated that between 40 – 70% of applied urea may be lost through leaching, immobilisation and volatilisation[2-4]. Increasing nitrogen use efficiency (NUE) of granular urea fertiliser is key in the maintenance of soil and plant health while also meeting global food demands.

The development of Enhanced Efficiency Fertilisers (EEFs), is an important goal, to increase the plant available nutrient amount available over time.[4].

Two studies are described involving two different formulation approaches to increase the efficiency of urea-based fertiliser. One approach involved blending the urea with lignite in various proportions to produce uniform granules[3]. A second novel approach involved using co-crystal noncovalent derivatives (NCDs) technology as a coating component of urea nitrogen fertilizer. These approaches both avoid polymer coatings on urea granules that produce microplastics as well as other potentially adverse effects.

Both fertiliser formulations were subjected to a series of evaluations including water dissolution, column leaching, nitrous oxide emissions, nitrate and ammonium in soils and limited plant growth trials. Both fertiliser formulations demonstrated significantly slower nutrient release in water compared to uncoated urea. Supporting evidence from silver beet pot trials and a strip plot field trial with corn, further demonstrated the potential benefits of both fertilisers in promoting plant growth.

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# Binary Polymer-Humic Soil Amendments as a Tool to Remediate Degraded Soils

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**ABSTRACT**

A number of polymer-based formulations were tested in laboratory and field experiments as soil ameliorants focused to combat soil erosion and enhance soil properties. Individual synthetic and natural polyelectrolytes were tested: polycation polydiallyldimethylammonium chloride (PDDA), polyanion hydrolyzed polyacrylonitrile (HYPAN), xanthan gum (XAN), and natural polyanions of humic substances (HS), as well as complex formulations presented by interpolyelectrolyte complexes (IPECs) and binary polymer-humate compositions. Humic substances (HS) are natural polyanions that are widely used as soil conditioners and biostimulants in agricultural technologies and have a potential to enhance to positive effects of other polymers on soil properties and plant growth. The objective of this study was to examine the effects on anti-erosion resistance, soil hydrophysical properties, ecotoxicity, and detoxication ability of a number of individual polymeric soil ameliorants and to reveal advantages of two-component formulations compared to individual polymers. Model experiments were conducted using soil samples different in texture, pH, humus content, and salinity. Ecotoxicity of polymer formulations was assessed using standard toxicity bioassays using cultures of bacteria *Escherichia coli*, the ciliate *Paramecium caudatum*, earthworms *Eisenia foetida*, and plant species.

PDDA-based formulations were the most effective to decrease manifestations of wind and water erosion, but in some cases demonstrated ecotoxicity. HYPAN- and XAN-based compositions showed the lack of toxicity in soil media, were capable of forming protective soil-polymer coatings, decreased loss of soil affected by wind and water flow, and improved soil hydrophysical properties. In heavy metal-spiked soil-polymer mixtures, combinations of polymers (PDDA, HYPAN and XAN) with natural humic biopolymers decreased the content of mobile Cu, Zn, Pb, and Cd species and mitigated the toxicity of heavy metals for plants and soil microbial community.

Differences in the sorption capacity of polymer compositions were related to their molecular structure. Polymer macromolecules bind to the surface of soil particles through hydrogen bonds, van der Waals interactions, and electrostatic bonds between negatively charged sites on the particles and the polymer. HSs typically bind metals via carboxyl groups and polycationic bridges. They also exhibit redox activity due to the presence of highly condensed aromatic structures rich in quinone/hydroquinone fragments, which also facilitates chelation and binding of metals.

The effects on soil hydrophysical properties were mainly governed by synthetic polyelectrolytes, whereas the effects on soil chemical and biological properties were influenced by HS. The advantages of two-component compositions compared to individual polymers are determined by the limiting factor for the sustainable soil functioning (hydro-physical properties, humus status, level of contamination, etc.).

**Acknowledgments**

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# The Synergistic Effect of Silicate and Calcium in Inhibiting Na+ Uptake: A Mechanism for Mitigating Salt Stress in Wheat

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**ABSTRACT**

Although exogenous silicon (Si) is known to alleviate the significant inhibitory effects of salt ion stress on wheat growth, its synergistic mechanism with calcium (Ca) remains unclear. This study employed a Box-Behnken design with three variables: silicon (Si; 0, 1, 2 mM), sodium ($Na^+$; 50, 150, 250 mM), and calcium ($Ca^{2+}$; 5, 15, 25 mM), totaling 17 experimental treatments to investigate their interaction on root peroxidase (POD) activity and ion homeostasis. Results demonstrate that medium Si enhances salt tolerance primarily by regulating ion uptake and reinforcing POD-mediated antioxidant capacity, and this effect is most effectively synergized with medium $Ca^{2+}$, whereas suboptimal $Ca^{2+}$ levels strongly inhibit Si efficacy. Under high $Na^+$ stress (250 mM), plant biomass and root growth were severely inhibited, as indicated by the most significant suppression observed in the absence of Si and under low $Ca^{2+}$ conditions, likely due to a lack of synergistic protection against membrane lipid peroxidation. In contrast, the combination of medium Si (1 mM) and medium $Ca^{2+}$ (15 mM) optimally sustained ion homeostasis and enhanced antioxidant capacity under medium salt stress (150 mM $Na^+$), as demonstrated by restricted shoot $Na^+$ accumulation (56.65 g/kg), reduced root MDA, and concurrently enhanced root POD and leaf chlorophyll, suggesting improved membrane stability. High Si (2 mM) applied with low $Ca^{2+}$ significantly promoted plant growth, as shown by root length, root fresh weight, and plant height being 1.9, 1.8, and 1.3 times greater, respectively, than those in the medium Si-$Ca^{2+}$ combination at medium Na+ stress, potentially via activated growth pathways. However, Si benefits were negligible under the low $Ca^{2+}$ combination at high $Na^+$ stress (250 mM $Na^+$ + 5 mM $Ca^{2+}$), implying $Ca^{2+}$ deficiency may restrict Si mediated tolerance mechanisms. These findings provide crucial insights into Si-$Ca^{2+}$ interactive mechanisms and a theoretical basis for developing targeted Si amendment strategies to improve crop productivity in saline soil.

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# Technological Breakthroughs for Enhancing Nutrient Use Efficiency in Bio-based Coated Controlled-Release Fertilizers

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**ABSTRACT**

Controlled-release fertilizers (CRFs) can improve nutrient utilization efficiency, reduce waste and environmental pollution, aligning with green agricultural development. Developing bio-based coating materials has become a primary research focus. However, the preparation presents multiple challenges. Their susceptibility to water absorption, poor compactness, and insufficient toughness. Coating process technologies require refinement, and nutrient release struggle to precisely match crop requirements. Thus, enhancing the controlled-release quality and achieving efficient nutrient utilization have become critical issues.

To address these challenges, research has achieved innovations in coating modification, processes and specialized fertilizers for precise nutrient matching.

The superhydrophobic modification technology is based on the formation of an air layer at the water-coating interface, which effectively blocks water penetration. This innovation increased the hydrophobicity of the coating material by 90.5%. Furthermore, technologies for interpenetrating network densification and self-healing toughening were developed, reducing the coating porosity by 20.6%. These technologies overcome the bottlenecks in bio-based coatings. The development of multi-stage dynamic variable coating and bio-based material photocuring coating process technologies has addressed issues such as uneven coating and high coating material consumption, enabling efficient industrial production. Rapid and uniform coating curing under light conditions was achieved, overcoming the challenges of uneven coating and susceptibility to tearing in traditional processes for large particles. The curing time was shortened from 5 minutes to 3–5 seconds. Specialized CRFs for crops address low nutrient-release precision. Through multi-formula compounding and double-layer coating, they significantly improve the synchronization between nutrient release and crop demand. This increases nutrient use efficiency by over 10 percentage points, enabling one-time fertilization at sowing to meet the nutrient needs of crops throughout their growth cycle.

In summary, these technological breakthroughs have achieved efficient nutrient utilization in bio-based CRFs and elucidated the mechanisms, providing theoretical and technical support for industrial application.

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# Effects of Chlorella Application on Soil Quality and Crop Productivity in Saline–Alkali Soils of Xinjiang, China

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**ABSTRACT**

Saline–alkali soils severely limit agricultural productivity in arid regions of northwest China. In addition to conventional irrigation and drainage engineering, biological amendments may provide complementary approaches for improving soil quality and crop performance. *Chlorella*, a unicellular green alga characterized by rapid growth, high organic carbon and nitrogen contents, and strong stress tolerance, has emerged as a promising bio-amendment for saline–alkali soil improvement.

In this study, both soil incubation experiments and field trials under crop cultivation were conducted to evaluate the effects of *Chlorella* application on soil chemical and physical properties as well as crop growth in typical saline–alkali soils. Under non-planting conditions, *Chlorella* dry powder was applied at four rates (0.05–0.20 g $kg^{-1}$ dry soil). Higher application rates significantly reduced soil pH (0.13–0.35) and electrical conductivity (5.4–30.1%), while increasing soil organic carbon (6.6–21.0%) and total nitrogen (5.7–8.5%). *Chlorella* amendment markedly altered soil physical properties, decreasing the one-dimensional vertical water infiltration rate by 58.1–62.4% and significantly enhancing soil aggregate stability, as indicated by increases in mean weight diameter, geometric mean diameter, and water-stable aggregates (>0.25 mm). Structural Equation Modeling further revealed that improvements in soil structure and salinity were primarily mediated by enhanced soil carbon and nitrogen pools.

Field experiments with sunflower and wheat demonstrated that *Chlorella* application significantly improved soil fertility, reduced salinity, and promoted crop growth throughout the growing season. Among the application methods tested, foliar spraying produced the strongest effects, increasing crop biomass accumulation and grain yield by approximately 22–29% in sunflower and markedly improving yield components in wheat.

Overall, *Chlorella* amendment effectively enhanced saline–alkali soil quality by simultaneously regulating soil salinity, structure, and water infiltration processes, thereby promoting crop productivity in arid agroecosystems.

**Keywords:** micro-algal; salt-affected soils; soil physical properties; water infiltration; crop yield formation

**Acknowledgments**

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# Potential of Mg-Fe Layered Double Hydroxide as a Slow-Release Phosphorus Fertilizer Compared with Commercial Recycled Sources

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**ABSTRACT**

Layered double hydroxides (LDHs), widely studied for phosphorus (P) recovery from wastewater, have recently been proposed as slow-release fertilizers. This study evaluated the fertilizer potential of P-loaded Mg–Fe LDH compared with commercial recycled P sources (vivianite and struvite) and a conventional soluble fertilizer (triple superphosphate, TSP). A 28-day incubation experiment was conducted in two P-deficient soils (acidic and near-neutral) using $CaCl_2$-extractable P as an indicator of readily available P. Soil pH, $Fe^{2+}$ concentrations, and redox potential were also monitored to assess chemical changes influencing P dynamics. Synthetic Mg–Fe LDH consistently exhibited a slow-release pattern in both soils. In acidic soil, struvite and TSP released high soluble P early (0.167 and 0.109 mg P $L^{-1}$ on day 2) but declined sharply by day 28, whereas Mg–Fe LDH gradually increased to the highest final concentration (0.100 mg P $L^{-1}$). This trend coincided with a pH rise from 6.6 to 7.0, suggesting LDH's buffering effect facilitated sustained P availability. In near-neutral soil, Mg–Fe LDH maintained controlled release, rising from 0.127 mg P $L^{-1}$ on day 2 to 0.188 mg P $L^{-1}$ by day 14, then stabilizing near 0.178 mg P $L^{-1}$ at day 28, contrasting with struvite and TSP, which peaked early and declined. Vivianite showed minimal release in both soils. These results demonstrate the potential of Mg-Fe LDH as a sustainable slow-release P source that can enhance P availability while supporting nutrient management strategies.

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# Optimising Nitrogen Nutrition Index (NNI) for maize cultivation with controlled release fertilizer treatments guided by UAV remote sensing technology

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## ABSTRACT

**Purpose:** Efficient nitrogen (N) management is essential for improving maize yield and resource use efficiency. The nitrogen nutrition index (NNI) is a common tool to assess crop N status. However, its response under controlled-release fertilizer (CRF) management is still not clear. This study evaluated how different N fertilizer types affect maize NNI. It also tested the use of UAV multispectral data for accurate N monitoring.

**Methods:** A two-year field experiment with five N treatments was conducted to evaluate the effects of fertilizer type on the maize's CNDC and the NNI at the V6, VT and R2 growth stages. CNDCs and NNI models were developed from leaf area index (LAI) and aboveground biomass (AGB) and compared using Akaike (AIC) and Bayesian (BIC) information criteria. A gradient boosting decision tree (GBDT) model was built from UAV multispectral data.

**Results:** CRFs significantly improved N distribution uniformity and model accuracy. CRF had stronger effects on LAI than on AGB, but NNI based on AGB better reflected actual N balance. Based on accumulated N deficit conditions characterised using AIC and BIC information criteria, a fertilisation range of 150-225 kg $ha^{-1}$ was determined. Furthermore, a CNDC model established using measured NNI_AGB was implemented to utilise unmanned aerial vehicles for predicting NNI. The GBDT model based on UAV multispectral data and by screening sensitive variables through variance inflation factors (VIF) achieved the highest accuracy and stability (R2 =0.88, RMSE =0.04, nRMSE=4.98%).

**Conclusion:** CRF management combined with UAV-based monitoring offers an effective way to diagnose maize N status. This approach supports precise N application and sustainable agriculture.

**Keywords:** Nitrogen Nutrition Index; Controlled release fertilizer; Critical N Dilution Curve; UAV remote sensing

**Acknowledgments**

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# Regulatory Effects of Soil Acidification Amendments Application on Enzyme Activity, Aggregates and Rice Yield in Red Soil

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**ABSTRACT**

To investigate the effects of soil acidification amendments on microorganisms, enzyme activities, aggregates, porosity, and rice yield in red soil, a 3-year fixed-position field experiment with rice was conducted in this study, which set six treatments: no fertilizer (X0), NPK fertilizer (X1), lime + NPK fertilizer (X2), high-activity acidification amendment (1) + NPK fertilizer (X3), high-activity acidification amendment (2) + NPK fertilizer (X4), and high-activity acidification amendment (3) + NPK fertilizer (X5). Indicators including soil microbial biomass carbon and nitrogen, enzyme activities, aggregates, porosity, and rice yield were determined.The results showed that compared with X1 treatment, other treatments increased soil pH by 0.29-0.9 units under different treatments, among which X4, X2, and X5 treatments significantly increased by 0.61, 0.72, and 0.9 units, respectively. For aggregates with particle size >2 mm, X2 treatment significantly increased by 32.8%, while X4 and X5 treatments significantly increased by 14.30% and 16.76%, respectively. X3 treatment significantly increased the activities of BG, CBH, and NAG enzymes in the tested soil by 131.22%, 19.45%, and 20.44%, respectively, and X4 treatment exhibited an overall better enhancement effect than X3, with increases of 132.83%, 47.96%, and 30.27%, respectively.CT scanning results indicated that X4 treatment had a significant effect on the surface area, porosity, and volume of soil aggregates with different depths (0-15 cm shallow layer, 20-55 cm middle-deep layer) and different particle sizes (>1 mm, 1-0.5 mm, <0.5 mm), following a consistent pattern. In the middle-deep layer, the surface area of aggregates with various particle sizes (>1 $mm^2$, 1-0.5 $mm^2$, <0.5 $mm^2$) in X4 treatment was 747.14%-1013.08% higher than that in X1 treatment, the porosity increased significantly, and the volume increased by 384.09%-1014.39%.The thousand-grain weight of X4 treatment was higher than that of other treatments, and the yield was significantly increased by 17.7% compared with X1, reaching 6576 $kg \cdot ha^{-1}$. In summary, both high-activity acidification amendments and lime combined with NPK fertilizer can improve the physicochemical properties of red soil and enhance enzyme activities. Among them, high-activity acidification amendment (2) + NPK fertilizer shows the best effect, which can provide a favorable environment for rice growth by increasing soil pH, improving red soil physicochemical properties, enhancing enzyme activities, promoting the formation of macroaggregates and increasing the number of pores, thereby achieving yield increase. This study provides a technical References for improving the fertility of red soil paddy fields and high-yield and high-quality rice cultivation.

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# Soil nitrogen deficiency and heat stress drive tissue-specific metabolic reprogramming governing nitrogen utilization in soybean

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## ABSTRACT

**Introduction:** Soil nitrogen (N) deficiency is a primary constraint to crop productivity worldwide, and climate change is exacerbating this challenge through increased incidence of high temperature (HT) stress. The interaction between soil N availability and heat stress fundamentally alters how plants acquire and utilize N from soil, yet the metabolic mechanisms coordinating whole-plant N utilization under these combined stresses remain poorly understood.

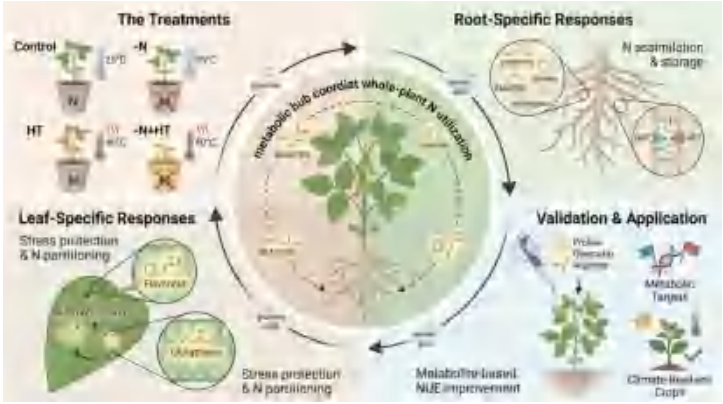
**Objectives:** This work examined how N deficiency and HT stress, individually and in combination, drive distinct metabolic reprogramming in roots and leaves that regulates plant N utilization. We hypothesized that roots and leaves exhibit complementary N metabolic profiles in response to N deficiency, and that combined heat stress reveals unique N utilization hubs that determine whole-plant resilience.

**Methods:** Soybean plants were subjected to control, soil N deficiency (-N), HT, and combined -N+HT conditions. We assessed whole-plant physiological responses, with emphasis on N uptake from soil and N assimilation efficiency. Untargeted metabolomic profiling of roots (the primary soil interface) and leaves was performed, with targeted analysis of N-containing metabolites. Machine learning identified key metabolic regulators of N utilization under stress.

**Results:** Combined -N+HT severely inhibited plant growth and N utilization, reducing shoot length (67%), root fresh weight (52%), photosynthetic efficiency (47%), and tissue N content compared to control. Metabolomic analysis revealed tissue-specific N utilization strategies driven by soil N status: under -N alone, roots prioritized N assimilation and recycling, accumulating glutamate, proline, and aspartate, while maintaining expression of high-affinity N transporters to enhance N scavenging from soil. Under HT alone, leaves enhanced N remobilization into protective compounds (flavonoids, glutathione). Under combined -N+HT, roots focused on amino acid metabolism and N storage (proline, asparagine) to cope with limited soil N supply, while leaves directed N toward stress protection, indicating prioritized allocation of soil-derived N to protection over growth. Machine learning identified proline, flavonoids, and specific amino acids as top regulators coordinating soil N utilization with physiological resilience. Exogenous application of these metabolites partially restored N utilization efficiency under stress.

**Conclusion:** Soybean employs distinct N utilization strategies in roots and leaves to manage soil N deficiency and heat stress, with tissue-specific partitioning of soil-derived N. The identified metabolites represent hubs coordinating utilization of soil N under combined stress, offering targets for breeding climate-resilient crops with enhanced nitrogen use efficiency for sustainable production in N-deficient soils.

**Keywords:** Soil nitrogen deficiency, nitrogen use efficiency, soybean, combined stress, climate change, tissue-specific N metabolism, plant-soil interactions



# Enhancing Nitrogen Utilization and Profitable Corn Production While Minimizing Environmental Impact

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**ABSTRACT**

Impressive strides in the quantity and quality of grain production to meet world demands have been made thanks in large part to nitrogen (N) inputs, but often it has come at the expense of environmental degradation. As we try to solve the conundrum of environmentally sustainable and profitable agricultural production, it is clear that more needs to be done to better understand the impact of N management on crop production and its environmental footprint. Deliberate efforts have been devoted to establishing agronomic N best management practices (N-BMPs) for corn production. However, the same emphasis to determine the environmental outcomes of N-BMPs is lacking. Thus, studies of N-BMPs that integrate various N loss pathways with agronomic outcomes are chronically insufficient to determine whether N-BMPs to improve corn production are concomitantly sufficient to mitigate N loss. A number of studies, located on well-drained coarse-textured soils and on poorly drained fine-textured soils with subsurface drainage in the Upper Midwest region of the USA, will be summarized. The studies measured season-long $NO_3$ leaching, $NH_3$ and $N_2O$ emission along with corn grain yield, total crop N uptake, and residual soil N after harvest. Enhanced practices combining N source, rate, time, and application method were evaluated against traditional practices. The coarse-textured site also had no cover-crop, winter rye cover-crop, and kura clover living-mulch. Generally, crop N uptake and grain yield showed a quadratic-plateau response to N rate. Reducing N rates below the economic optimum resulted in less productivity and profitability and small reductions in environmental N loss. Applying N rates above the economic optimum resulted in nominal or no increase in productivity, reduced profitability, and increased environmental N loss. Using enhanced efficiency N (polymer-coated urea), often reduced N loss and maintained productivity and profitability. Splitting the N application in-season had agronomic and environmental advantages in the coarse-textured soil, but had generally only agronomic advantage in the fine-textured soil. Because of poor growth, the rye cover crop largely had no effect on agronomic or environmental outcomes, but kura clover substantially reduced $NO_3$ leaching, slightly increased $NH_3$ losses, but reduced grain yield, diminishing potential adoption by farmers. While the dual goal of improved corn production and environmental protection are attainable, precipitation after fertilization largely influenced N loss and diminished the otherwise attainable benefits of refining N management practices. Overall, the findings of these studies highlight that targeting the economic optimum N rate for corn production is also an environmentally sustainable practice, but realistic expectations must be set, realizing that adverse unpredictable weather conditions can ultimately negatively influence the outcome.

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# Fertilizer-Driven Nitrate Availability and Waterlogging Resilience in Canola: Benefits and Micronutrient Trade-offs

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## ABSTRACT

Waterlogging alters soil nutrient dynamics and constrains crop productivity. We evaluated four fertilization strategies—an inorganic chemical fertilizer (Base) and three organic amendments (biochar + Base, chicken manure + Base, fish blood & bone meal + Base)—in *Brassica napus* (canola) to assess impacts on nitrogen (N) availability and plant performance under waterlogging. The experiment was conducted in pots using Grey Chromosol (Australian Soil Classification) which is prone to seasonally waterlogging. Pre-waterlogging soil nitrate nitrogen ($NO_3^-$–N) was the strongest predictor of post-waterlogging biomass across spring- and winter-type cultivars (Spearman $\rho > 0.73$, $p < 0.01$). Inorganic fertilization significantly elevated pre-waterlogging $NO_3^-$ concentrations ($R^2 = 0.80$, $p < 0.001$), outperforming the organic amendments. Soil $NO_3^-$ was positively associated with shoot N uptake ($R^2 = 0.24$, $p = 0.016$) and biomass accumulation ($R^2 = 0.19$, $p = 0.036$), supporting a mechanistic pathway where fertilizer-driven nitrate enrichment before waterlogging is strongly associated with higher shoot N and greater biomass under stress. Furthermore, inorganic fertilizer also altered Fe and Mn accumulation in plant shoots. These results demonstrate nitrate's central role in maintaining biomass under waterlogging and highlight a practical trade-off: inorganic fertilizer enhances resilience via nitrate supply while increasing shoot Mn accumulation. The findings offer practical guidance on fertilizer timing and type selection to strengthen nitrogen resilience in waterlogging-prone canola systems.

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# Rapid induction of $NH_4^+$ efflux in rice roots under high-ammonium stress and its association with varietal differences in ammonium tolerance and ammonium-utilization efficiency

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## ABSTRACT

Ammonium ($NH_4^+$) efflux serves as a crucial mechanism in root responses to ammonium toxicity. Our previous investigations have demonstrated that both protein N-glycosylation and auxin homeostasis play pivotal regulatory roles in modulating $NH_4^+$ efflux, leading to the identification of key regulatory genes including AtVTC1, AtWRKY46, AtPIN5, and OsVTC1.3. However, fundamental questions remain unresolved, particularly concerning the initiation and recovery kinetics of $NH_4^+$ efflux under stress conditions and its relationship with ammonium use efficiency (AUE) and ammonium tolerance. To address these questions, we conducted pharmacological analyses using rice root protoplasts subjected to transient high-$NH_4^+$ treatment. Our results revealed that acute ammonium stress promptly induces sustained $NH_4^+$ efflux, potentially mediated by aquaporins, ABC transporters, and potassium channels. Screening of 99 rice cultivars demonstrated a significant negative correlation between $NH_4^+$ efflux and both root ammonium tolerance and AUE ($P < 0.01$), establishing efflux as a key limiting factor for nitrogen use efficiency. Furthermore, probenecid-mediated inhibition of efflux enhanced $NH_4^+$ uptake by 23.65% in high-efflux cultivars, underscoring the regulatory potential of $NH_4^+$ efflux. This study provides novel insights into the mechanisms underlying plant adaptation to ammonium toxicity and establishes a molecular framework for developing nitrogen-use-efficient crops through manipulation of $NH_4^+$ efflux pathways.

**Keywords:** $NH_4^+$ efflux, ammonium stress, ammonium use efficiency, rice cultivars

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# ISOPENTENYL TRANSFERASE3 activation triggers root ammonium hypersensitivity via the cytokinin ARR10/ARR12 CAP1 signaling pathway

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**ABSTRACT**

High ammonium ($NH_4^+$) inhibits primary root (PR) elongation in plants, but the underlying regulatory mechanisms remain poorly understood. In this study, we screened the PSKI015 activation-tagged mutant library and identified a novel dominant mutant, named Ammonium Sensitive 3D (amos3D), which shows increased sensitivity to high $NH_4^+$ in terms of PR elongation. Gene cloning revealed that amos3D is an overexpression mutant of IPT3, a gene involved in cytokinin biosynthesis. Pharmacological and genetic analyses revealed that the sensitivity of amos3D PR to high $NH_4^+$ is due to elevated levels of the active cytokinins iP and tZ. We furthermore identified ARR10 and ARR12, type-B ARRs, as key transcription factors in the cytokinin-mediated inhibition of PR elongation under high-$NH_4^+$ stress. Using CUT&RUN, yeast one-hybrid, and dual-luciferase assays, we show that ARR10 and ARR12 directly bind to the promoter of CAP1, a tonoplast-localized kinase, repressing its transcription. This repression reduces $NH_4^+$ transport from the cytosol to the vacuole, leading to increased Gln/Glu ratios, and enhanced $NH_4^+$ toxicity. Collectively, our identification of AMOS3 as a key regulator inhibiting PR growth under high $NH_4^+$ through the cytokinin-dependent ARR10/ARR12-CAP1 pathway not only reveals a novel $NH_4^+$-sensing mechanism but also offers promising agronomic potential for optimizing root architecture and improving nitrogen-acquisition efficiency in crops under ammonium-based fertilization systems.

Keywords: Ammonium, IPT3, cytokinins, ARRs, ammonium metabolism

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# The role of the nitrate transporter NRT1.1 in plant iron homeostasis and toxicity on ammonium

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**ABSTRACT**

Ammonium (NH4+) is toxic to root growth in most plants, and NH4+ toxicity has been linked to disruptions in plant Fe homeostasis. However, only a few genes have been linked to the disruption of Fe homeostasis under NH4+ nutrition, and pathway details have as yet to be resolved. Here, using RNA-seq analysis and RT-qPCR, we explore the response of different genes expressed in the roots of Fe-replete and Fe-starved Arabidopsis plants under NH4+ conditions. The Nitrate Transporter 1.1 (NRT1.1) gene, known to code for a dual-affinity nitrate transporter, but not other NRTs genes, was specifically induced in Fe-replete plants in response to NH4+ provision. NRT1.1 antagonizes NH4+-dependent Fe accumulation, and this antagonism requires NO3- supply. Constitutively expressing NRT1.1 confers higher NO3- uptake and reduces NH4+-dependent Fe accumulation by increasing pH in the rhizosphere. Building on previous evidence establishing the involvement of root Fe accumulation in the root growth response to elevated NH4+, our study shows that NRT1.1-mediated nitrate uptake curtails symptoms of NH4+ toxicity under elevated NH4+ and in the presence of NO3-, by increasing rhizospheric pH, offering new insights into possible pathways for improving the tolerance to NH4+ toxicity in plants.

**Keywords:** ammonium toxicity, iron, nitrate, NRT1.1, root growth

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# Regulation of the GS–GOGAT–GDH Pathway under Ammonium Nutrition: Mechanistic Insights into Nitrogen Assimilation and Utilisation Efficiency in Oil Palm Seedlings

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## ABSTRACT

Nitrogen (N) is a fundamental macronutrient vital for sustaining plant growth, metabolism, and productivity. Among tropical crops, oil palm (Elaeis guineensis) is particularly nitrogen-demanding, yet its enzymatic mechanisms of nitrogen assimilation have received little scientific attention. In plantation practice, ammonium-based fertilisers are widely used due to their lower cost compared to nitrate-based sources. Nonetheless, the biochemical responses of oil palm to ammonium fertilisation remain inadequately characterised. This study examined the activities of key nitrogen-assimilating enzymes in oil palm roots and their influence on amino acid biosynthesis and biomass production under varying ammonium chloride (NH4Cl) fertilisation rates. We hypothesised that (1) nitrogen-assimilating enzyme activities in root tissue would peak under high ammonium fertiliser input; (2) Enzyme activities could serve as potential physiological indicators of nitrogen use efficiency (NUE). Three-month-old oil palm seedlings were supplied with four levels of N input: zero (0 g N), low (4.5 g N), medium (9.0 g N), and high (18.0 g N), and grown for eight months. Root tissues were analysed for nitrate content, total amino acids, and the activities of nitrate reductase (NR), nitrite reductase (NiR), glutamine synthetase (GS), glutamate synthase (GOGAT), and glutamate dehydrogenase (GDH). Increasing ammonium availability induced a metabolic shift from the NR/NiR-mediated nitrate reduction pathway toward the GS–GOGAT–GDH ammonium assimilation cycle. GS activity peaked under low $NH_4Cl$ input, reflecting the incorporation of $NH4^+$ into glutamine, but declined under higher inputs due to negative feedback inhibition. GOGAT activity was strongly suppressed at high $NH_4Cl$ rates, while glutamate dehydrogenase activity increased under elevated ammonium, functioning as a detoxification mechanism to maintain nitrogen homeostasis. Among treatments, medium $NH_4Cl$ application yielded the most balanced GS–GOGAT–GDH profile and the highest total amino acid accumulation. However, this treatment did not produce the greatest biomass. Both above- and below-ground biomass increased with higher N input, with the high-fertiliser treatment yielding the highest biomass (0.47 kg) compared to the medium treatment (0.39 kg), though the difference was not statistically significant. These findings indicate that enhanced enzymatic activity and amino acid synthesis do not necessarily translate into proportional biomass gains. Moderate ammonium application appears to promote a balanced and efficient nitrogen metabolism, optimising biochemical performance without inducing metabolic stress. In contrast, excessive fertilisation may enhance overall biomass production but reduce biochemical efficiency, triggering detoxification pathways. Further studies integrating both root and leaf enzyme profiling are needed to establish enzymatic activity as a reliable non-destructive indicator of NUE in oil palm.

# Responses of Rice Production, $NH_3$ and $N_2O$ Losses to Biochar Application at Different Growth Season of Rice-Wheat Rotation

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**ABSTRACT**

Biochar (BC) application affects gaseous nitrogen (N) losses mainly via nitrous oxide ($N_2O$) emission and ammonia ($NH_3$) volatilization from paddy soils. However, in rice-wheat rotation systems, the impact of BC that being incorporated into soils at the initiation of different crop planting seasons on the two aforementioned gaseous N losses remains unclear. Therefore, we conducted a 2-year (2020 and 2021) soil column experiments with 5 t $ha^{-1}$wheat straw BC investigate the effects of BC that being applied during the rice season (BC-R) or wheat season (BC-W) and to on rice grain yield, $N_2O$ emissions, and $NH_3$ volatilization from rice paddy soil with three N supply levels (low: 160 kg N $ha^{-1}$, medium: 200 kg N $ha^{-1}$ and high: 240 kg N $ha^{-1}$). BC application during the wheat season had a significant effect on rice grain yield ($P < 0.05$), with the most pronounced response observed in 2020. Under 350 kg N $ha^{-1}$, the N200+BC-W treatment produced 12.4% higher grain yield than the N200 treatment. Moreover, wheat-season BC application significantly enhanced cumulative grain yield over the two-year period ($P < 0.05$). Notably, the effects of BC application on soil $N_2O$ emissions and $NH_3$ volatilization exhibited interannual variation, depending on the different crop planting seasons. Compared to N160, the N160+BC-R treatment significantly reduced $N_2O$ emissions by 15.9% in 2020. BC application during the wheat season in 2021 significantly decreased $N_2O$ emissions in the N160+BC-W and N200+BC-W treatments, with reductions ranging from 36.7% to 53.6% relative to N fertilization alone. In 2021, $NH_3$ volatilization in the N200+BC-R decreased by 28.7% compared with the N200, whereas the N200+BC-W achieved a greater reduction of 54%. BC application in this study did not yield significant reductions in net global warming potential (GWP) or greenhouse gas intensity (GHGI). Nevertheless, the N200+BC-W in 2021 showed a decreasing trend in both GWP and GHGI. Overall, the effect of BC on gaseous N losses was strongly influenced by the application season and the experimental year. in conclusion, the N200+BC-W represents the optimal management strategy for both emission reduction and high yields.

**Keywords:**Biochar；Paddy Soi；N use efficiency；GHG；Crop Production

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# MGP1-mediated Mitochondrial ROS Homeostasis Couples Carbon Metabolic Switching with Nitrate Adaptation

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**ABSTRACT**

Carbon–nitrogen (C/N) metabolic coordination is fundamental for plant growth. Mitochondria are central hubs of carbon oxidation and energy production. Electron transport across the respiratory chain and the associated generation/scavenging of reactive oxygen species (mROS) are crucial for maintaining mitochondrial metabolic stability. However, the contribution of mROS to plant energy metabolism and broader carbon metabolic reprogramming, and how such reprogramming feeds into plant nitrogen adaptation, remains largely unresolved.

Here, we characterized an uncharacterized glutathione S-transferase (GST) family member, namely Mitochondrial GST Protein 1 (MGP1). MGP1 homologs from unicellular algae to vascular plants localize to mitochondria, and high-resolution imaging shows MGP1 co-localizes with inner-membrane markers. Loss of MGP1 causes elevated mitochondrial swelling, indicating compromised mitochondrial integrity. Transcriptome profiling reveals robust upregulation of genes involved in mitochondrial organization, together with induction of compensatory ATP-producing carbon pathways (glycolysis and the pentose-phosphate pathway). In contrast, energy-demanding carbon sinks, including cell wall remodeling and sulfur-rich secondary metabolism, are consistently repressed, implying the role of MGP1 in shifting from growth/defense investment toward survival-oriented carbon utilization.

Notably, multiple high-affinity nitrate uptake/transport and nitrate-starvation signaling genes are constitutively upregulated in the *mgp1* mutant, suggesting that mitochondrial dysfunction-driven C-reprogramming triggers a persistent nitrogen-hunger state. Consistently, *mgp1* displays enhanced primary-root growth under low-nitrate conditions. Inhibition of mETC complexes I/III, applying mito-targeted antioxidants, or genetic accumulation of a peroxidase into mitochondria all markedly alleviate low-nitrate root growth inhibition, indicating that excessive mROS is a key determinant of nitrate starvation sensitivity.

We propose that MGP1 acts as a negative regulator of low-nitrate root growth by promoting ROS accumulation close to the inner-membrane mETC domain. mROS levels thereby tune the balance between mitochondrial and cytosolic carbon metabolism modes, which in turn gates nitrate uptake and assimilation programs. Our study implies a tight coupling between mROS homeostasis, carbon metabolic switching, and nitrate-response outputs, highlighting an unappreciated contribution of mitochondria to plant nitrogen adaptation.

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# Comparative Analysis of Arbuscular Mycorrhizal Fungi Characteristics in the Rhizosphere and Roots of Wheats with Different Ploidy Levels under Saline-Alkaline Soils

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**ABSTRACT**

Unlike diploid staple crops such as rice (*Oryza sativa* L.) and maize (*Zea mays* L.), modern wheat (*Triticum aestivum* L.; AABBDD) is a typical allohexaploid crop, derived from the natural hybridization between tetraploid wheat (*Triticum turgidum* L.; AABB) and its diploid ancestor *Aegilops tauschii* Coss. (DD). Early studies have shown that hexaploid wheat exhibits higher adaptability to saline-alkaline soils compared to tetraploid wheat, which is closely associated with the salt tolerance mechanism mediated by *TaHKT1;5-D* induced $Na^+$ efflux. However, whether soil microorganisms, regarded as the "second genome" of plants, are involved in the differential adaptation of wheat with different ploidy levels to saline-alkali soils remains unexplored. In this study, a set of genetic materials capable of simulating natural evolutionary processes was used, including artificially synthesized hexaploid wheat T093SHW, its diploid parent Aegilops tauschii T093, and tetraploid wheat LDN. Taking arbuscular mycorrhizal fungi (AMF), a symbiotic microorganism involved in the uptake of nitrogen and phosphorus and the improvement of plant nutrient use efficiency, as the entry point, we found that the abundance, community structure, and species richness of symbiotic AMF in the roots of hexaploid T093SHW in saline-alkali soils were similar to those of tetraploid LDN. However, at the operational taxonomic unit (OTU) level, T093SHW evolved the ability to be colonized by specific AMF taxa. More importantly, T093SHW showed a stronger capacity to recruit AMF in the rhizosphere. This study elucidates a novel mechanism underlying the enhanced adaptability of hexaploid wheat to saline-alkali soils, and provides a theoretical References for promoting the "coordinated adaptation between wheat and saline-alkali soils" by taking AMF as a bridge.

**Keywords:** Saline-alkaline soils; Different ploidy wheat; Arbuscular mycorrhizal fungi (AMF); Community diversity; Symbiosis

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# Phenolic BNIs drive shifts in nitrifying community structure and function leading to suppressed nitrification in an acidic soil

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**ABSTRACT**

Intensive fertilization drives strong nitrification in acidic agroecosystems, accelerating nitrogen loss and $N_2O$ emissions. We tested whether the chemical class of biological nitrification inhibitors (BNIs) predicts efficacy and microbiome response by comparing six BNIs in an acidic-soil microcosm over 24 days: three phenolic acids (methyl 3-(4-hydroxyphenyl) propionate, syringic acid, methyl ferulate) and three fatty-acid BNIs (linoleic acid, linolenic acid, methyl linoleate). Nitrification rates were quantified, nitrifier gene abundances (AOA-*amoA*, AOB-*amoA*, NOB-*nxrA*/*nxrB*) were tracked by qPCR, and community composition and co-occurrence networks were resolved by high-throughput sequencing. Phenolic BNIs consistently suppressed nitrification, whereas fatty-acid BNIs showed little or no inhibition. Phenolic treatments produced an early decline in AOB-*amoA* and a sustained reduction in NOB-*nxrB* throughout incubation; in contrast, fatty-acid BNIs minimally affected *amoA* or *nxrB* and only transiently decreased *nxrA*. Community shifts under phenolic BNIs included reduced *Nitrosospira* cluster 3a.1 within AOB and *Nitrospira bockiana* within NOB-*nxrB*, alongside sparser, more competitive networks in which a single *Nitrospira* hub was replaced by multiple smaller hubs across nitrifier groups. These changes indicate selective down-weighting of efficient nitrifiers positively associated with process rates while permitting expansion of less efficient taxa (e.g., *Ca.* Nitrosocosmicus), thereby decoupling ammonia from nitrite oxidation and lowering community nitrification potential. Our results show that BNI chemical structure governs nitrifier network architecture in acidic soils, providing a mechanistic basis for deploying phenolic BNIs to limit nitrification and $N_2O$ risk.

***Keywords:*** Nitrification; Biological nitrification inhibitor; Co-occurrence networks; Network modules; Acidic soils; Nitrifier community

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# Phenolic acid methyl esters mitigate $N_2O$ emissions by inhibiting ammonia-oxidizing bacteria and stimulating $N_2O$ reducers in a moderately acidic soil

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## ABSTRACT

Biological nitrification inhibitors (BNIs) can reduce soil nitrous oxide ($N_2O$) emissions, but the inhibition strength depends on the type of BNIs and on soil properties. Phenolic acid methyl esters belong to a class of BNIs that occur in substantial amounts in plant tissues. However, the effects of these BNIs on moderately acidic soils with high $N_2O$ emissions remains unclear. Here, a soil incubation experiment was conducted to investigate the effects of three phenolic acid methyl esters on $N_2O$ emission, soil physicochemical factors, the abundance of nitrifying and denitrifying genes, and microbial communities in a moderately acidic soil. The results show that the three BNIs all significantly reduced $N_2O$ emission, and the inhibition rate of methyl cinnamate (CM) and methyl ferulate (FM) was about twice that of methyl 3-(4-hydroxyphenyl) propionate (MHPP). The three phenolic acid methyl esters significantly reduced the abundance of AOB-*amoA* while increasing the abundance of *nosZ* and the ratio of *nosZ*/(*nirK* + *nirS*). High-throughput sequencing revealed that the three BNIs altered soil microbial communities by promoting the abundance of Proteobacteria, particularly those belonging to the genera of *Massilia* and *Burkholderia-Caballeronia-Paraburkholderia*. Further, random forest and structural equation modelling indicated that these BNIs reduced $N_2O$ emissions by modifying the key factors of pH and dissolved organic carbon (DOC), targeting Proteobacteria, and affecting the abundance of AOB, *nirS*, and *nosZ*, thus suppressing nitrification and promoting complete denitrification. Our findings demonstrate that the application of phenolic acid methyl ester BNIs presents a promising nitrogen management strategy to mitigate $N_2O$ emissions from moderately acidic soils.

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# Direct Inhibition of Ammonia Monooxygenase by Biological Nitrification Inhibitor 1,9-decanediol Induces Energy Conservation and Stress Response in Nitrosomonas europaea

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**ABSTRACT**

1,9-Decanediol, a biological nitrification inhibitor (BNI) identified from rice root exudates, effectively suppresses nitrification in both pure culture systems and soil environments. However, its physiological and transcriptional regulatory mechanisms against ammonia-oxidizing bacteria remain unclear. Here, we systematically investigated the model ammonia-oxidizing bacterium *Nitrosomonas europaea* through integrated physiological and transcriptomic analyses (RNA-seq). The results showed that 100 μg/mL 1,9-decanediol significantly inhibited nitrite production. The vitro enzymatic assays revealed that 1,9-decanediol directly targets ammonia monooxygenase (AMO) in a reversible manner. Additionally, 1,9-decanediol slowed the growth of *N. europaea* without causing significant membrane damage or increased cell mortality. Transcriptomic analysis further demonstrated downregulation of genes involved in oxidative phosphorylation and energy-consuming biosynthetic pathways, such as amino acid metabolism and ribosomal proteins, whereas genes associated with the two-component system, chemotaxis, and RND efflux pumps were upregulated. These findings indicate that under the stress of BNI 1,9-decanediol, energy metabolism and biosynthesis process in *N. europaea* cells are disrupted, thereby activating multiple stress response and escape signals for feedback regulation. This study provides a theoretical basis for developing BNI-based environmentally friendly strategies for nitrification management.

***Keywords:*** Biological nitrification inhibitor, 1,9-decanediol, *Nitrosomonas europaea*, AMO, Transcription response

# Rice promotes abundance of nitrogen fixing bacteria in paddy field soils

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**ABSTRACT**

Sufficient nitrogen supply is essential to maximize rice yield. Nitrogen fertilizer has been used to supply N to rice, but due to increasing concerns on environmental degradation, rice production with reduced nitrogen supply without losing yield is required for future sustainability. Iron-reducing bacteria (IRB) have been documented as major nitrogen-fixing microorganisms in paddy field soils. As IRB abundance is affected by carbon. it is possible that rice cultivation also affects IRB abundance in paddy field soils. To test this, we developed a microcosm system using field-collected paddy soil to enable controlled evaluation of rhizosphere IRB and established a qPCR-based quantification method. We found that rice cultivation increases IRB abundance in paddy field soils. We also found that the extent of increase depends on rice cultivars. Applying this system to diverse rice accessions, we collected dataset of extents of IRB abundance increase for individual rice cultivars and the dataset was used for genome-wide association analysis. Genomic regions associated with IRB abundance were identified (Lin et al 2025), and within each LD block, genes carrying variants predicted to alter protein function and showing strong statistical association ($p \leq 0.001$) were selected as candidate genes that affect IRB abundance in soils. CRISPR–Cas9 knockout lines are being generated for these genes, and mutants have been obtained for several genes. These mutants will be evaluated to determine their effects on IRB abundance. At the congress we will present updates of our project. We believe that the results will facilitate elucidation of rice genetic factors involved in regulating rhizosphere IRB and provide a basis for integrating microbial functions into nitrogen management strategies.

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# Effects of Biological Nitrification Inhibitors on Maize Yield and Nitrogen Utilization in Red Soil

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## ABSTRACT

Biological Nitrification Inhibitors (BNIs) is the exudates from plant rhizosphere, 1,9-decanediol is a typical biological nitrification inhibitor from rice roots, promotes root growth in Arabidopsis and plays an important role on soil nitrification and nitrogen-loss reduction. However, the effects of Biological Nitrification Inhibitors (BNIs) on crop production and nitrogen（N）utilization in red soil in field are limited.

A field experiment was conducted and a typical BNIs 1,9-decane diol was used to investigate the effects of BNIs on maize yield and nitrogen use efficiency in red soil. Seven treatments were set: T1 (No, no N fertilization ), T2 (Conventional N application, 225 kg N /ha,), T3 (20% N reduction, 180 kg N /ha), T4 (Conventional N + 2% 1,9-decane diol), T5 (Conventional N + 5% 1,9-decane diol), T6 (20% N reduction + 2% 1,9-decane diol), and T7 (20% N reduction + 5% 1,9-decane diol). The maize growth and yield, N uptake, N translocation and N use efficiency were analyzed.

The results showed that, the addition of BNIs significantly increased maize yield and nitrogen use efficiency in red soil. Compared to conventional N application T2,20% N reduction (T3) decreased maize yield by 1.86%, but the reduction was not statistically significant.Under conventional N application, applying different concentrations of BNIs (T4 and T5) increased maize grain yield by 5.02% and 9.84% and biomass by 19.96% and 21.60%. Under the 20% N reduction condition, applying different concentrations of BNIs (T6 and T7),maize grain yield increased by 8.50% and 3.00%, and biomass increased by 14.39% and 5.58%. Among all treatments, the maize yield of T5 and T6 are the highest, T6 showed the best effect on yield increasing. Addition BNIs increased the maize N accumulation and N translocation from vegetative organs to grain. Under conventional N application and under N reduction,BNIs increased the plant N accumulation by 4.24%~8.87% (T4 and T5) and decreased it by -0.36% and -0.37% (T6 and T7)respectively. Simultaneously, the N translocation of BNIs from vegetative organs to grains increased by 14.26%~32.94% under conventional N application (T4 and T5) and by 12.38%~24.94% under N reduction (T6 and T7). The nitrogen agronomic efficiency (AE) increased by 20.94%~21.25% (T4 and T5) and 35.63%~48.10%(T6 and T7), respectively, while the nitrogen recovery efficiency (RE) increased by 49.65%~54.25% (T4 and T5) and 51.07%~59.71% (T6 and T7), respectively. Among all treatments, T5 and T6 showed the best effect on the N utilization increasing.

In conclusion, biological nitrification inhibitors (BNIs) can significantly enhance maize yield and nitrogen fertilizer use efficiency by promoting nitrogen accumulation and translocation in maize grown in red soil. BNIs addition maintains good performance both for maize yield and N use efficiency even under reduced 20% nitrogen application, demonstrating the potential as a green practice for synergistically increase both crop production and nitrogen use efficiency and achieving nitrogen fertilizer reduction.

**Keywords:** Biological nitrification inhibitors(BNIs); Nitrogen use efficiency; Yield, Maize; Red soil

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# Multivariate Analysis of Biomass Production and Nutritional Efficiency of Marandu Palisadegrass Fertilized with Bioinputs

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## ABSTRACT

Nitrogen, although essential for the development of grasses, exhibits short residence time in the soil and high application costs, particularly in tropical regions. Moreover, nitrogen fertilizer use efficiency is low; it is estimated that approximately 50% of the applied N is lost through volatilization or leaching, contributing to environmental impacts such as soil acidification and water eutrophication (BANGER et al., 2017). Inoculation with plant growth-promoting bacteria (PGPB), such as *Azospirillum brasilense* and *Bacillus* spp., has emerged as an effective strategy to enhance the agronomic performance of forage grasses, especially under tropical conditions where nitrogen demand is high. The objective of this study was to evaluate the association between PGPB and nitrogen rates on nutritional efficiency and biomass production of *Urochloa brizantha* cv. Marandu Palisadegrass. The experiment was conducted under field conditions in a pasture-establishment area of *Urochloa brizantha* cv. Marandu during the 2023/2024 and 2024/2025 growing seasons, at the Experimental Farm ofUNESP (21°27’ S, 5l°36’ W; 42l m altitude). The soil was classified as a dystrophic Ultisol. Pasture establishment included the application of l0 kg ha_1 of pure viable seeds broadcast and incorporated, along with 200 kg ha_1 of 4-30-10 (N-P2O5-K2O) fertilizer. The experimental design was a randomized block design with four replicates. Treatments involving nitrogen fertilization (urea) and foliar bacterial inoculation were: T1) References (zero N and no bacteria), T2) 80 kg ha_1 N, T3) 40 kg ha_1 N, T4) T3 + *Azospirillum brasilense* Ab-V5 + Ab-V6 (AZ), T5) T3 + *Bacillus* S26 (S26), T6) T3 + *Bacillus* N72 (N72), T7) T3 + AZ + S26 + N72, T8) AZ + S26 + N72, T9) AZ, T10) S26, T11) N72. The combined canonical axes (Can1 + Can2) explained 86% to 95% of the variation in the integrated dataset across the two growing seasons. This outcome demonstrated that inoculation with *Azospirillum* and *Bacillus* S26 and N72, whether applied individually or in co-inoculation, enhanced plant metabolic activity, increased nutritional efficiency, and improved dry mass production. Co-inoculation, particularly when associated with the reduced N rate, yielded the best performance, sustaining high dry mass production even under declining residual soil fertility. In contrast, mineral nitrogen fertilization alone showed reduced efficiency over time. Thus, the use of microbial bioinputs represents a sustainable and effective strategy to maximize productivity in tropical pasture systems.

**Acknowledgments**

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# Developing Machine Learning Protocol for Optimizing Nitrogen Nutrition in Rice

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**ABSTRACT**

Nitrogen is a vital macronutrient that significantly affects rice growth, grain yield, and quality. The widespread use of N without proper management can lead to economic losses and environmental harm through leaching, volatilization, and greenhouse gas emissions (Swathy et al., 2024). To address these issues, the present study aimed to develop a machine learning-based protocol to optimize nitrogen nutrition in rice by combining graded nitrogen levels with foliar applications of Nano Urea and remote sensing derived vegetation indices. The field experiment was conducted during the 2023 and 2024 Rabi seasons at the Wetland Farms of Tamil Nadu Agricultural University, Coimbatore. The trial was arranged in a Split Plot Design with eleven graded nitrogen doses (0–150 kg N $ha^{-1}$, representing 0–100% of the recommended dose) in the main plots and four foliar nutrition treatments in the subplots: Nano Urea (16% N) at 0.7%, sprayed at active tillering, panicle initiation, and heading, along with a no-foliar-nitrogen control and each replicated three times. Growth, physiological, and yield attributes were recorded at critical growth stages, while high-resolution multispectral images were captured using a DJI Phantom 4 platform to compute key vegetation indices (NDVI, NDRE, GNDVI, GCVI, MCARI, SAVI, and EVI) as proxies for crop vigour and nitrogen status. The results indicated that both graded nitrogen levels and Nano Urea foliar sprays, as well as their interaction, significantly affected plant height, tiller number, panicle length, and grain yield. The highest yield (6228 kg $ha^{-1}$) was achieved with 100% of the recommended nitrogen combined with a Nano Urea spray at active tillering, while the control (0 kg N $ha^{-1}$, no foliar nitrogen) produced the lowest yield (3695 kg $ha^{-1}$). Importantly, 70% of the recommended nitrogen combined with Nano Urea spray at active tillering resulted in yields statistically similar to the 100% nitrogen treatment, suggesting that a 30% reduction in nitrogen input can be achieved without compromising productivity. Spectral analysis showed strong positive relationships between nitrogen level, chlorophyll content, and canopy reflectance, with NDVI and GCVI exhibiting the highest correlations with plant nitrogen content across stages. Linear regression models identified EVI as the most reliable predictor of nitrogen status during early growth, while NDVI performed better at panicle initiation, with good agreement between observed and predicted values. Based on these relationships, a Python-based Nitrogen Management Calculator was developed to offer real-time, index-based recommendations for nitrogen sufficiency or deficiency. Overall, the study demonstrates that integrating nanofertilizer-based foliar nutrition, multispectral sensing, and machine learning provides a strong framework for site- and stage-specific nitrogen management in rice, enhancing nitrogen use efficiency, supporting more sustainable and input-efficient rice production systems.

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# Functional Complementarity in Cover Crop Mixtures Shapes Subsoil Carbon–Nitrogen Partitioning via Maize Reuse of Root Channel Legacies

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## ABSTRACT

Biodiversity can enhance ecosystem functioning not only through interactions but also through lasting legacies that shape future resource use. In agroecosystems, these legacy effects are extensively studied in topsoil but remain largely unexplored in subsoil layers despite their critical role in nutrient acquisition, drought resilience and carbon storage. Here, we combined a $^{13}C$–$^{15}N$ dual-labeling field experiment with microbial community profiling and metaproteomics to investigate how cover crop diversity influences carbon (C) and nitrogen (N) dynamics across soil depths (0-30 and 30-60 cm). We identified root channel legacies as a key pathway through which cover crop mixtures affect the fate of plant-derived C and N in deep soil layers. Cover crop mixtures that combine deep- and shallow-rooting species enhanced the recovery of plant-derived $^{13}C$ and $^{15}N$ in empty root channels relative to deep-rooting monocultures, with stronger effects in the subsoil (30–60 cm) than in the topsoil (0-30 cm). Reuse of legacy root channels by maize intensified microbial C and N processing in rhizosphere hotspots, with subsoil legacy processes dominating maize N acquisition. Microbial structural and functional dynamics further showed that cover crop mixtures reshaped microbial community composition and upregulated protein pathways involved in carbohydrate and N metabolism, with amplified responses in reused channels. Importantly, different mixtures expressed distinct functional effects, demonstrating that biodiversity effects in agroecosystems are functionally heterogeneous rather than uniform. Together, our findings expand biodiversity–ecosystem functioning theory by identifying subsoil legacies as an overlooked dimension of ecological memory. By imprinting the subsoil microbiome through root channel, plant diversity enhances and diversifies crop nutrient capture, suggesting improved resilience to increasing climatic fluctuations by global change.

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# Intercropping enhances soil nitrogen mineralization through C/N ratio-induced microbial network synergy

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## ABSTRACT

Soil nitrogen (N) mineralization is a critical ecological process that plays a significant role in maintaining soil fertility and sustainability of agroecosystems. Legume//cereal intercropping, particularly in wheat//faba bean systems, has been demonstrated to enhance the soil's nitrogen supply capacity. Nonetheless, previous studies have rarely addressed how intercropping affects soil net nitrogen mineralization rates and their temporal dynamics, as well as the associations with the soil carbon-to-nitrogen ratio, nitrogen-transforming enzyme activities, microbial community structure, and particularly the properties of microbial interaction networks. Here, we conducted a continuous wheat//faba bean intercropping field experiment and performed in-situ soil-core incubation over two growing seasons to assess monthly variations in soil ammonification, nitrification, gross mineralization and net mineralization rates during the growing season (December to May), and subsequently investigated the regulators of soil nitrogen mineralization. We systematically examined how intercropping drives N mineralization through stoichiometric, enzymatic and microbial pathways by integrating in-situ incubation, enzymatic profiling, high-throughput sequencing and microbial co-occurrence network analysis. We found that intercropping increased soil N mineralization rates, with a peak increase of 154.8% in March. Intercropping increased the soil C/N ratio by up to 11.62%, and enhanced the activities of N-acetyl-β-D-glucosaminidase and leucine aminopeptidase by 39.25% and 45.26%, respectively. Microbial network analysis showed higher proportions of positive links in the intercropping system than in Monocropped crops, reaching 95.6%. Path analysis revealed that intercropping increased soil N mineralization mainly through elevated soil C/N ratio induced microbial resource reallocation to N-acquiring enzymes and enrichment of nitrifying taxa, which stimulated the nitrification process (increase of 183.00%) and consequently enhanced overall N mineralization. In conclusion, crop diversity-driven changes in soil C/N stoichiometry induced a cooperative microbial network and enriched keystone functional taxa, which promoted mineralization efficiency. A new mechanism elucidating the positive crop diversity effect on N cycling is proposed.

**Keywords:** Intercropping; Soil nitrogen mineralization; Microbial community; Enzyme activity; Soil C:N ratio; Nitrogen cycle



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# Short term impacts of biochar on vine tissues total carbon and nitrogen and their stable isotope compositions as well as berry yield in two vineyards in Southeast Queensland of subtropical Australia

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## ABSTRACT

Regenerative viticulture (RV) is a vineyard management approach that aims to increase vineyard soil carbon (C) and restore vineyard soil health, improve ecosystem services and mitigate against extreme climatic events.

Biochar is one potential RV tool, however its impact on subtropical vineyard soils is minimal. This study aimed to investigate the short-term impacts of biochar application on total carbon (C), total nitrogen (N) and their isotope compositions ($\delta^{13}C$ and $\delta^{15}N$) in vine plant tissues (young and mature petioles, young and mature leaves, rachis and berries) during spring and harvest sampling at two Southeast Queensland vineyards of subtropical Australia.

Pine biochar (650°C pyrolysis) was applied at 0, 5.0, 10.0 and 20.0 t $ha^{-1}$ to the vine rows (VR) soil at two vineyards, Nuova Scuola (NS, clay-loam soil) and Ballandean Estate (BE, sandy soil) in August 2023. Soil and vine tissues were sampled two months later in spring at ~70% capfall, with the second sampling being the day before harvest about 5 months after biochar application. The total C, total N and their isotopic compositions($\delta^{13}C$ and $\delta^{15}N$) on the soil and vine tissues were measured.

The isotopic compositions responses strongly differed significantly with the site, with the yield parameters mostly unaffected over one growing season. In sandy soil, the 5 t $ha^{-1}$ biochar application enriched $\delta^{13}C$ in vine tissues and berries, indicating increased plant water-use efficiency (WUE), but 20 t $ha^{-1}$ biochar application improved soil microbial N transformations, producing enriched $\delta^{15}N$ in vine tissues and berries as well as evidence of potentially better yield and lower individual berry weight. In clay loam soil, biochar effects were not so significant, with negative $\delta^{13}C$ values of continual lower WUE, however increased $\delta^{15}N$ at 10 t $ha^{-1}$ was optimal for N use efficiency (NUE) with little discernible effect on the berry yield.

Biochar applications affected the soil – vine isotopic coupling primarily through soil microbial and vine physiological processes, with responses strongly governed by the site-specific soil texture. Dual isotopic analysis of using both $\delta^{13}C$ and $\delta^{15}N$ provided a sensitive diagnostic tool to fingerprint the impacts of biochar applications on soil microbial functioning and vine nutrient efficiency under the framework of regenerative viticulture (RV).

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# Temporal dynamics of biological nitrification inhibition efficiency in wheat under varying degrees of plant growth realism

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## ABSTRACT

Plant root–secreted compounds can act as biological nitrification inhibitors (BNIs), suppressing soil nitrification and improving nitrogen use efficiency, thereby reducing nitrogen losses through greenhouse gas emissions and leaching in agricultural systems. Despite their potential, the key drivers of BNI efficiency remain poorly defined, particularly in wheat. Addressing this knowledge gap is critical for optimizing nitrogen management, mitigating environmental impacts, and enhancing crop productivity.

In this study, we developed and applied multiple complementary approaches to quantify BNI efficiency and assessed the effects of plant growth conditions (hydroponic versus soil), developmental stages (tillering, stem elongation, booting, and flowering), and genotype (high-, mid-, and low-BNI wheat lines). A novel integrated BNI index revealed higher BNI efficiency under hydroponic conditions compared with soil, suggesting that soil mechanical constraints and rhizosphere microbial interactions modulate root exudation patterns.

BNI activity was observed across all genotypes and increased with plant developmental stage, consistent with rising nitrogen demand. Integrated metabolomic and microbial community analyses identified key mechanisms underpinning the BNI phenotype, including the exudation of specific benzoxazinoid compounds and the selective suppression of archaeal and bacterial ammonia-oxidizing populations in the rhizosphere.

Our findings demonstrate that BNI is a significant and regulated ecosystem function in wheat, driven by genotype-dependent root exudation that varies with growth conditions and developmental stage. Specific root metabolites differentially influenced rhizosphere microbial communities, thereby controlling nitrification rates and nitrogen availability. This work advances our understanding of BNI regulation in wheat and provides a foundation for developing sustainable nitrogen management strategies to reduce nitrogen losses and improve agricultural efficiency.

**Keywords:** crop, BNI, nitrifier, nitrogen use efficiency, sustainable agriculture

# Hyperspectral imaging explains the leaf base to tip nitrogen spatial dynamics in maize

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**ABSTRACT**

Context: Robust prediction of maize leaf nitrogen concentration (LNC) is essential for optimizing nitrogen (N) management strategies aiming for reducing fertilizer input and maintaining crop yield stability. However, how the spatial distribution patterns of N within individual leaves are associated with N deficiency and developmental senescence has not the fully understood. Advanced hyperspectral imaging (HIS) technologies, provide a high-throughput and non-destructive way to monitoring the spatial variability in LNC, which has the potential of offering new insights into explaining the spatiotemporal dynamics from super high-resolution hyperspectral scans across individual millimeters of a leaf surface. Objective: This study aimed to elucidate the physiological responses of N partitioning patterns in leaves to N stress and developmental senescence using HIS, and to achieve nondestructive, fine-scale monitoring of leaf N status through a band optimization algorithm. Methods: Field experiments were conducted in Inner Mongolia during the 2023 and 2024 growing seasons, involving maize cultivars subjected to varying N levels. HSI of the latest fully expanded leaves and the oldest leaves (V9 stage) were captured at vegetative (V9, V12) and reproductive (VT, R1) stages. LNC was measured in six pre-defined segments along individual leaf length. The stability of published spectral indices and the optimized spectral indices for spatial LNC prediction mapping were compared. Results: LNC exhibited a decreasing gradient from the tip to the base in the latest fully expanded leaves, whereas an inverse pattern was observed in the oldest leaves. In both cases, the N distribution displayed symmetrical patterns centered on the leaf venation. Excessive N supply and developmental senescence did not alter these spatial distribution trends. Compared to published indices, the optimized spectral indices (OSIs) significantly improved the accuracy of spatial LNC mapping along the leaf. OPT-NPDI demonstrated the highest stability (R2 = 0.80, RMSE = 0.27%). Conclusions: Neither excessive N application nor leaf senescence altered the intrinsic spatial distribution pattern of N within maize leaves. Senescence appeared to stabilize the spatial distribution of LNC. The accuracy of OPT-NPDI and its insensitivity to variations in bandwidth highlight its applicability across sensors with varying spectral resolutions. Significance: This study advances the application of HSI for fine-scale, non-destructive monitoring of leaf N status by developing a modeling framework. It provides methodological support for the broader deployment of hyperspectral imagers in precision nutrient phenotyping and management.

**Acknowledgments**

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# From methodological to mechanistic frameworks: assessing BNI efficiency by integrating varying levels of plant growth realism

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**ABSTRACT**

Quantifying biological nitrification inhibition (BNI) efficiency in crops is critical for advancing sustainable nitrogen management. However, current BNI phenotyping is constrained by methodological inconsistencies and limited mechanistic understanding of how plant growth conditions (hydroponics vs. soil), developmental stages and genotypes (high- vs. low-BNI wheat lines) interact to shape observed BNI outcomes, particularly in wheat.

Here, we establish an integrated methodological-mechanistic framework to assess BNI efficiency across contrasting plant growth conditions (hydroponics vs. soil), developmental stages, and genotypes (high- vs. low-BNI wheat lines). We combine complementary direct and indirect approaches, including culture-based bioassays (ammonia-oxidising archaea (AOA) and bacteria (AOB)) of root exudates, soil nitrification assays, molecular characterisation of rhizosphere nitrifier communities, and metabolomic profiling of root exudates, to determine how varying levels of plant growth realism drive BNI expressions.

Our results demonstrate that BNI efficiency differed between soil- and hydroponically grown plants, indicating distinct biochemical and microbial interaction regimes. Metabolomic profiles revealed growth condition and developmental stage dependencies in root exudate composition, providing mechanistic insight into observed discrepancies among BNI estimation approaches. BNI effects were demonstrated across tested genotypes, the capacity to discriminate between high- and low-BNI lines varied among BNI estimating approaches, indicating differential sensitivity to metabolite-mediated versus microbially mediated inhibition processes. Higher BNI lines maintained plant nitrogen acquisition, indicating no apparent trade-off between BNI expression and plant N uptake. Plant developmental stage affected BNI efficiency, but stage-dependent patterns diverged across approaches, highlighting trade-offs between mechanistic specificity, temporal resolution, and ecological relevance.

Together, these findings demonstrate that BNI efficiency is a plant strategy arising from coordinated shifts in plant metabolism, rhizosphere microbial communities, and growth context. By explicitly linking methodological choice to mechanistic interpretation, this framework provides a basis for more interpretable, comparable, and standardised BNI phenotyping, supporting both crop breeding strategies and nitrogen management applications.

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# The contribution of N derived from deep-rooting cover crop mixture to soil N dynamics and subsequent maize nutrition

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## ABSTRACT

The globally highly problematic nitrogen (N) deposition in natural ecosystems is largely derived from losses of mineral fertilizer-derived N from agroecosystems. Thus, alternative strategies to tighten the N cycle in crop production are urgently needed, specifically for crops with high N demand such as maize (*Zea mays* L.). Cover crops (CC) can contribute to this through enhanced N input and stabilization within the soil N pool. Few studies, however, have fully quantified the N input into the soil from CC and the subsequent re-use of this N by the following main crop. CC species should bring N in organic form into the soil, ensure ongoing N transformation and turnover, and enable the release of available N for the following cash crop upon demand. However, there might be trade-offs between these optimal traits and individual species are unlikely to achieve all of them. Therefore, we aim to assess the effects of three different cover crop mixture (CCM, legume/grass, legume/brassica and brassica/grass) with deep- and shallow-rooting species on N input into soils, microbial N transformation and N turnover in top (0-30 cm)- and subsoils (30-60 cm), including the implication for subsequent maize N nutrition. To generalize or differentiate our results, we conducted our $^{15}N$ leaf-labeling field experiment at three sites with different soil types implying three soil fertility levels. The results revealed that CCM significantly increased N mineralization compared to fallow at the site with lowest soil fertility, but no significant CCM effect was identified at sites with higher soil fertility. The CCM containing deep-rooting brassica demonstrated a discernible beneficial impact on the N uptake of subsequent maize crop. In consequence, the main crop maize profited most from the pre-crops, showing highest CCM-derived $^{15}N$ uptake, under lower soil fertility, whereas maize growing on high-fertile soils exhibits a pReferences for the uptake of nutrients from the native soil. Consequently, the use of CCMs is of highest benefit in low-fertile soils and can only urgent be recommended there. Among them, whenever crop rotation allows, the use of brassica-based mixture will promote subsequent crop N uptake from the CCMs, and thus allows for reduced fertilizer N application. In consequence, the use of CCM represents a viable and effective management strategy for crop farming systems.

# Variation Patterns and Influencing Factors of Fine Root Uptake of Different Nitrogen Forms with Stand Age in Cunninghamia lanceolata

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## ABSTRACT

Nitrogen (N) uptake of forest trees vary across different developmental stages, which exerts a significant impact on tree growth and carbon sequestration capacity. This study focused on Chinese fir (Cunninghamia lanceolata) plantations, the world's largest monoculture plantations, and selected stands of 11, 21, 24, 31, 42, 52, 58, and 68 years of age. Two in situ $^{15}N$ labeling experiments were conducted: an in situ hydroponic experiment and an in situ soil experiment. The objectives were to investigate how the fine root N uptake capacity for different N forms (both as an inherent trait and under natural conditions) changes with stand age and to identify the influencing factors.

The results showed that, regardless of the experimental condition, the uptake rates of ammonium ($NH_4^+$) and glycine by fine roots decreased with increasing stand age. This decline might be attributed to the reduced N demand in the later growth stages of the plantation, where the strategy for N acquisition shifts from direct root investment to a "cooperative outsourcing" model, potentially enhancing interactions with soil microorganisms. In contrast, the uptake rate of nitrate ($NO_3^-$) exhibited a unimodal pattern with stand age, peaking at 42 years. This pattern is likely the combined result of changes in fine root nitrate transporter expression, energy supply, tree N demand, and soil N availability. Furthermore, the complete ability to absorb glycine was only detected in the fine roots of 31- and 42-year-old stands, which may be related to energy supply and microbial competition.

Collectively, these findings reveal the patterns and underlying mechanisms of the age-dependent shifts in the N uptake strategies of Chinese fir fine roots, thereby providing a crucial scientific basis for the future management of plantations.

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# Nitrogen-induced modulation of whole-plant transpiration under atmospheric drought

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## ABSTRACT

Nitrogen (N) deposition can significantly influence plant hydraulic cycling through modifying plant functional traits, biomass allocation and resource use. Under scenarios of increasing N deposition and atmospheric drought, it is thus crucial to understand how nitrogen affects plant transpiration as vapor pressure deficit (VPD) rises for predicting ecosystem responses, i.e., water and carbon exchange to climate change. Particularly, grassland communities dominated by C3 or C4 plants may respond differently due to their distinct photosynthetic pathways, which influence water and N use efficiency under varying environments. Here we combine a controlled gravimetric chamber and an experimental field study to quantify plant responses to N addition and rising VPD levels. Our chamber study revealed higher N levels reduced transpiration sensitivity to rising VPD at both leaf and whole-plant scales. Our field study demonstrated this reduced sensitivity was due to N-induced decreases in stomatal conductance and, somewhat counterintuitively, belowground biomass allocation, which collectively suppress water transportation and plant transpiration. Moreover, in chamber study whole-plant transpiration decreased with high N levels for C3 species, reflecting a trade-off between water and N use efficiency. In contrast, C4 species maintained high whole-plant transpiration as N levels rose due to their simultaneous high water and N use efficiency and sharp increases in plant productivity. Together our studies suggest under rising atmospheric drought scenarios, N differentially modulates leaf-level and whole-plant transpiration of C3 and C4 grass species. Future studies should predict how these differences drive the hydrological and carbon cycling, particularly with changing relative abundance of C3 and C4 species under climate change.

**Keywords:** Nitrogen Addition, Vapor Pressure Deficit (VPD), Whole-Plant Transpiration, C3 and C4 Grassland Species, Hydrological and Carbon Cycling

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# Nitrogen, manganese, iron and carbon resources acquisition are potential functions of wild rice Oryza rufipogon core rhizosphere microbiome

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**ABSTRACT**

Rhizosphere microbial communities are shaped by soil chemical properties, while how soil chemistry influence the core members recruited by plants remains unclear. We investigated the core rhizosphere microbiome of wild rice by comparing plants growth in three natural reserves (in situ) with those transplanted and cultivated ex situ for more than 40 years in soils of the same type but with different chemical characteristics. Using generalized joint attribute modeling (GJAM), we identified 44 amplicon sequence variants (ASVs) consistently shared across sites, including 35 bacterial and 9 fungal ASVs. These taxa mainly belonged to *Actinobacteria*, *Chloroflexi*, *Firmicutes*, *Nitrospirae*, *Ascomycota*, *Basidiomycota* and *Rozellomycota*. Several bacterial ASVs—particularly those from *Haliangium*, *Anaeromyxobacter*, *Bradyrhizobium* and *Bacillus*—were significantly enriched in ex situ soils, suggesting a strong influence of soil chemical factors on core microbiome structure. Functional predictions indicated roles in nitrogen fixation, manganese oxidation, chemoheterotrophy and iron respiration, highlighting their potential contribution to nutrient utilization and plant growth. Our results demonstrate that soil chemical properties can differentially regulate the core microbial community in wild rice rhizosphere microbiome and should be considered when designing strategies for soil and crop improvement.

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# Developing an AI-based Precision Nitrogen Management Strategy for Corn

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**ABSTRACT**

The optimal nitrogen (N) rates vary significantly from field to field and from year to year, affected by genetics, environmental conditions and management practices. The primary goal of this research was to develop an innovative in-season nitrogen (N) recommendation strategy for corn (*Zea mays* L.) across the U.S. Midwest using stacking ensemble machine learning (ML) and multi-source data fusion. Forty-nine site-years of N rate experiments conducted across the U.S. Corn Belt were used to evaluate the performance of five individual ML algorithms (Random Forest Regressor (RFR), Support Vector Regressor (SVR), Extreme Gradient Boosting Regressor (XGBR), CatBoost Regressor (CBR), and Multi-Layer Perceptron (MLP)) and stacking regression (STR) for in-season corn yield prediction under different preplant and split N application conditions using the active canopy sensor data along with genetics, environmental and management information. These models were further evaluated for their prediction of yield responses to sidedress N application rates and in-season estimation of site-specific economic optimal N rate (EONR) across the U.S. Corn Belt. The results indicated that the stacking model performed consistently well across all datasets for corn yield prediction, demonstrating robustness ($R^2 > 0.85$ for validation dataset). Preplant N rate, Sidedress N rate and normalized difference red edge (NDRE) were identified as key variables for predicting corn yield. For EONR estimation, the stacking regression 2 model (STR2) using RFR, SVR, XGBR, CBR, and MLP as base estimators and linear regression as the meta estimator performed the best for the full dataset ($R^2$=0.82 and root mean square of error (RMSE)=27.50 kg N $ha^{-1}$). It is concluded that the stacking regression and multi-source data fusion framework is a promising strategy for in-season site-specific corn yield prediction and sidedress N recommendation. It can be improved by adding more plot and on-farm N experimental data collected across diverse environmental conditions to guide in-season site-specific N management in the U.S. Midwest. It can also be adapted and improved for different crops, regions and dynamic price environments using UAV and satellite remote sensing and more advanced ML models with user-friendly interfaces to make greater contributions to the improvement of N use efficiency, farm profitability and agricultural sustainability.

**Keywords:** Precision nitrogen management, In-season nitrogen recommendation, Remote sensing, Machine learning

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# Effects of Nitrogen and Phosphorus on $N_2O$ Emissions from Leymus Chinensis and the Underlying Microbial Mechanisms

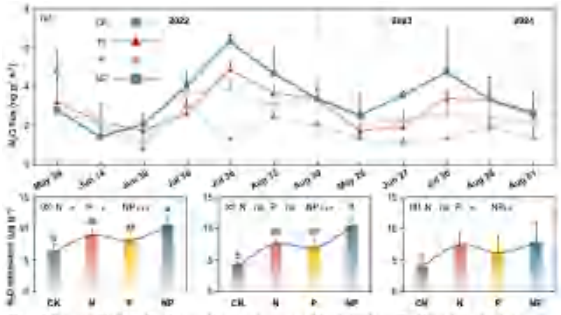
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## ABSTRACT

Nitrous oxide ($N_2O$) has a global warming potential equivalent to 298 times that of $CO_2$ over a 100-year horizon and is the dominant ozone-depleting substance in the 21st century. However, there are large uncertainties because it is still unclear whether all the sources have been well identified. Plant-mediated nitrous oxide ($N_2O$) emission is a crucial component of the terrestrial nitrogen cycle, yet its response to nitrogen (N) and phosphorus (P) nutrient additions and the microbial driving mechanisms remain unclear. This study aimed to investigate the $N_2O$ flux from *Leymus chinensis*, a dominant grass in temperate grasslands, to clarify the effects of N and P addition, and to reveal the roles of epiphytic and endophytic microbial communities.

A three-year field manipulation experiment was conducted to monitor the growing-season $N_2O$ flux from *L. chinensis*, with treatments including control (CK), N addition (N), P addition (P), and combined N and P addition (NP). Concurrently, laboratory incubations with non-sterilized and sterilized (simulating an endophyte-dominated, microbe-free internal environment) plant materials were performed to differentiate the contributions of epiphytic and endophytic microbes. Quantitative PCR (qPCR) was used to quantify the abundance of the epiphytic ammonia-oxidizing archaea (AOA) and bacteria (AOB) *amoA* genes, and the endophytic denitrification functional gene *cnorB*. High-throughput sequencing was employed to analyze the endophytic bacterial community structure.



The field experiment confirmed *L. chinensis* as a source of $N_2O$, with flux rates ranging from 0.8 to 6.3 ng $g^{-1}$ $h^{-1}$, peaking in late July coinciding with peaks in temperature and precipitation. Single N or P addition showed an increasing but non-significant trend, whereas NP co-addition significantly enhanced emissions (+63.1% in 2022, +142.3% in 2023). Laboratory incubations further confirmed the strong stimulatory effect of NP (non-sterilized: +179.6%; sterilized: +291.5%). N addition significantly increased the abundance of epiphytic AOA and AOB; P had a significant effect only on AOA. NP treatment increased AOA abundance by 212.7%. Sterilization attenuated microbial effects, but N addition still significantly increased *cnorB* abundance (+241.7%) and the Shannon index. NP addition markedly altered the composition of key denitrifying genera: e.g., increasing the relative abundance of *Brevibacillus* from 5.1% to 20.58% under non-sterilized conditions, and that of *Sphingomonas* from 2.22% to 44.54% under sterilized conditions. Random Forest analysis revealed that under non-sterilized conditions, epiphytic AOA abundance and the endophytic Shannon index were the most important variables for predicting $N_2O$ emissions. Under sterilized (endophyte-dominated) conditions, the relative abundance of endophytic *Sphingomonas* and the *cnorB* gene abundance became the dominant factors.

This study demonstrates that *L. chinensis* is a source of $N_2O$ in grassland ecosystems. Synergistic N and P addition strongly promotes $N_2O$ emissions, an effect far exceeding that of single nutrient additions. The mechanism involves the co-regulation by NP addition of both epiphytic ammonia-oxidizing microbes on plant surfaces and endophytic denitrifying microbial communities (specifically functional gene abundance and key genus composition) inside plants, thereby driving increased $N_2O$ production. This research highlights the necessity of considering plant-mediated emissions and the interactive effects of N and P nutrients underpinned by microbial mechanisms when assessing greenhouse gas budgets in grassland ecosystems.

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# Effects of plant hormone on microbial community in soil under conservation tillage

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## ABSTRACT

The complex network of interactions between plants and microbial communities play a vital role in regulating nutrient cycling, plant health, and ecosystem function, which are critical for maintaining ecological balance and sustaining agricultural productivity(Trivedi et al. 2020; Philippot et al. 2024). The rhizosphere provides an ideal environment for a diverse microbial community, which can be regarded as one of the most composite microbial ecosystems on earth. In the rhizosphere, plant roots secrete sugars, organic acids, coumarins, benzoxazinoids, plant hormones to regulate the rhizosphere micro-environment and recruit plant growth-promoting rhizobacteria to cope with various biotic and abiotic stresses(Sasse et al. 2018) (Yu et al. 2020).

Plant hormones are important signal molecules produced in very low concentrations but have diverse functions in cell elongation, cell differentiation, organogenesis, reproduction, and responses to abiotic and biotic stresses. Plant hormones are classified into nine categories, including encompasses auxins (IAA), cytokinins (CK), strigolactones (SL), brassinosteroid (BR), gibberellins (GA), ethylene (ET), abscisic acid (ABA), jasmonic acid (JA), salicylic acid (SA). Plant hormones—in particular, IAA is considered to be one of the most key regulators in regulating plant growth, shaping plant microbiota, and protecting plants from pathogens (Kou et al. 2022; Nakano et al. 2022). The major define phytohormones of SA and JA have been extensively studied in their function in plant – microbe interactions. The epiphytic and endophytic root microbiome community composition appears to be strongly driven by SA accumulation/insensitivity mutants (Kniskern et al. 2007; Lebeis et al. 2015). In addition, exogenous SA also application affected bacterial composition in bulk soil, suggesting that the effect of SA on microbial communities is independent of plant signals (Lebeis et al. 2015). Exogenous treatment with JA has recently been shown to increase Arabidopsis rhizosphere alpha diversity along with an enrichment of several potentially beneficial microbial taxa(Carvalhais et al. 2013). SLs are known not only as plant hormones, but also as molecular signals facilitators specific plant symbioses(Mashiguchi et al. 2021). The nodule number has been shown to decrease in strigolactone biosynthesis mutants in pea, soybean, and M. truncatula (Rehman et al. 2022; Van Dingenen et al. 2023; McAdam et al. 2017). Additionally, exogenous rac-GR24 treatment could reverse the reduced nodule phenotype in ccd7 mutant and rms4-mutant lines in pea (Foo and Davies 2011; Foo et al. 2013). Phytohormones signaling and biosynthesis affect composition and abundance of plant microbiota, while the unraveled phytohormones-optimised microbiome recruitment mechanism requires further investigation.

n this study, we first investigated the molecular mechanisms of soil microbiome recruitment by the application of exogenous nine categories phytohormones. Three categories (IAA, ZT, and SL) markedly influenced microbial respiration and their structure and function in topsoil. The application of JA and SA marginally altered the dynamics of microbial populations. Four other phytohormones (GA3, ACC, EBL, and ABA) treatments were not affected the microbial metabolism and community assembly both in topsoil and subsoil. Amplicon sequencing identified 20,604 bacterial and 6,900 fungal amplicon sequence variants (ASVs) in the topsoil, and 16,743 bacterial and 3,573 fungal ASVs in the subsoil. Microbes in the surface soils were dominated by Proteobacteria, Actinobacteria, Chloroflexi, andAcidobacteria. It has been suggested that the higher abundance of Proteobacteria in the surface layer may be linked to elevated levels of carbon and nutrients. To discern disparities in microbial diversity among soil strata, we first determined the alpha diversity indices, including the Shannon index, Chao1 index and Simpson index, and beta diversity metrics such as the Bray-Curtis distance based on the amplicon data.

Our results indicated a decline in microbial alpha diversity under both JA and ZT treatments in topsoil and subsoil. In contrast, bacterial beta diversity (spatial variations) increased across both soil layers, whereas fungal beta diversity remained unchanged. Overall, our study provides clear evidence for plant hormones-driven microbiome assembly. Next, we aimed at modulating the plant hormone levels by the engineering of PGPBs to promote plant growth and development.

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# Towards Smart Fertilization: Building a Dynamic Rhizosphere $NH_4^+/NO_3^-$ Model under the GiP Framework for Drastically Improved NUE

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## ABSTRACT

Background

Current average nitrogen fertilizer use efficiency (NUE) is suboptimal, leading to significant environmental pollution.

Methods

As part of the Global Ion-Moleculeome Project (GiP), we are constructing a global "live dynamic functional database" (GiPDatabase). This database integrates large-scale NMT-derived imOmics data on crop-specific $NH_4^+/NO_3^-$ uptake dynamics under varied soil and climatic conditions.

Results

Machine learning models trained on this database can predict real-time crop nitrogen demand with high spatio-temporal resolution. Preliminary simulations indicate that this GiP-enabled "Smart Agriculture" module can effectively increase NUE and reduce nitrogen runoff.

# Crop improvement for nitrogen and phosphorus use efficiency in rice

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**ABSTRACT**

Poor agricultural nutrient use efficiency adds to the triple planetary crisis of pollution, biodiversity integrity and climate change, as most of the nitrogen (N) and phosphorus (P) inputs are lost to the environment. N/P use efficiency (NUE/PUE) is therefore a huge economic and environmental issue for sustainable agriculture. Rice is an ideal target to improve NUE/PUE in India due to its highest fertilizer consumption and huge genetic and genomic resources. We characterized the phenotype for NUE separately for urea/nitrate and identified some of the most contrasting genotypes among a thousand released Indian rice varieties. We also characterized the phenotype for PUE in popular Indian rices and found some common traits for both NUE and PUE. The late-germinating, late-flowering, long duration rice varieties assessed had higher yield and NUE/PUE than the early-germinating, early-flowering, short duration varieties, with only one exception each so far. The common high-ranking traits common for NUE and PUE were, photosynthetic rate at the reproductive stage, number of tillers, root–shoot ratio, culm thickness, leaf width of flag leaf, shoot biomass, and straw weight. Transcriptomic analyses of contrasting rice varieties for N-responsive genes associated with the NUE phenotype, QTLs and yield, revealed the genes/pathways associated with NUE. They include G-proteins, transporters, transcription factors (TFs), microRNAs (miRNAs), kinases and phosphatases. Though over 70% of the rice N-responsive genes contain G-quadruplex sequences (G4Qs), indicating epigenetic regulation, over 83% of the NUE-related genes lacked G4Qs, indicating their direct genetic regulation and potential for genetic improvement. Physiologically, high NUE is associated with better photosynthetic performance, transpiration efficiency and internal water-use efficiency, relative to low NUE in rice. We also found some common genes for nitrogen and phosphorus use efficiencies. We are currently genome-editing candidate genes for crop improvement of NUE/PUE in popular Indica rices. We also used comparative RNAseq of contrasting NUE genotypes to identify SNPs and are developing markers for alternative selection/breeding strategies for NUE.

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# The power of the less productive: understanding the links between diversity and belowground traits of wild, landrace and modern crops

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**ABSTRACT**

Crop genetic erosion has been a major concern to ensure the stability and resilience of agronomic systems. The widespread use of modern crop cultivars favoured by conventional agronomic practices have led to a steady decline in crop diversity over the last century. Furthermore, traditional varieties of crops (landraces) and non-domesticated crop wild relatives (CWRs) remain a large untapped pool of genetic diversity often dismissed because of their lower productivity compared to modern crops. Still, comparisons in the functional traits of crops and CWRs have emerged as a critical research direction to increase our understanding of how plant domestication syndromes have reshaped relationships among yield and plant traits. Plant root exudation constitutes the chemical interface through which plants communicate with the rhizosphere microbiome. The associations between plants and rhizosphere microbes influence their root system and belowground soil nutrient-acquisition strategies. These associations can help crops access nutrients beyond their root-depletion zone to different pools of resources such as recalcitrant or organic nutrient forms not normally easily available to the plant. We expect modern crop roots to have lower rates and diversity of exudation than their wild relatives, due to lower relative investment in these processes and lower genetic diversity, leading to less diverse crop rhizospheres. To explore this hypothesis, we designed an experiment to collect root exudates, rhizosphere soil and root tissue of 20 different modern crop species and their respective landrace and CWR varieties. We assessed root nitrogen content, exudate quantity and composition using untargeted metabolomics and characterised the composition and diversity of root-associated soil microorganisms. Studying relationships between domestication syndromes in root traits and nutrient acquisition strategies may reveal the possibility of new directions in breeding programs to achieve more efficient yet sustainable agricultural practices.

# Maintaining sulfur supply to rhizobia delays nodule senescence in soybean

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**ABSTRACT**

Symbiotic nitrogen fixation (SNF) in legume-rhizobia represents a sustainable and eco-friendly alternative to chemical nitrogen fertilizers in agriculture. Identifying key factors involved in nodule senescence, is crucial for enhancing SNF by effectively extending the lifespan of nodules. Here, we reveal that sulfur, an essential element for SNF, plays a major regulatory role in the senescence of soybean (*Glycine max*) nodules. Blocking sulfur input into the symbiosome by knocking out either sulfur transporter genes *SULTR2;1* or *SULTR3;5*, resulted in a significant decrease in glutathione levels. This reduction impaired the capacity for reactive nitrogen species scavenging, thereby accelerating nodule senescence. Notably, reducing reactive nitrogen species (RNS) production in rhizobia or increasing sulfur input in soybean nodules through genetic manipulation, can effectively mitigated high nitrogen-induced nodule senescence. Our findings demonstrate that SULTR-mediated sulfur input is a pivotal step in regulating nodule senescence, and provide new insights for developing strategies to enhance SNF in legumes by delaying nodule senescence.

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# One-time root-zone nitrogen application enhances nitrogen utilization and yield of faba bean by reducing nitrogen loss in the plateau of southwestern China

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**ABSTRACT**

Conventional split broadcasting (CSB) of nitrogen (N) fertilizer often leads to low N use efficiency (NUE), and substantial environmental N losses, threatening fragile ecosystems such as that in the plateau regions of southwestern China. A 2-year field experiment was conducted to explore the effect of one-time root-zone fertilization (ORZ) method on the production of faba bean (*Vicia faba L.*) in Yunnan Province, southwestern China. Two N application methods (CSB, ORZ) with 6 N rates (0, 36, 72, 108, 144 and 216 kg $ha^{-1}$) were involved in the experiment. The results showed that ORZ significantly enhanced faba bean yield by 5.8–11.3% and economic benefits by 11.4–17.6% compared to CSB at the same N rates. N agronomic efficiency (NAE) and N apparent recovery efficiency (NARE) were also increased by 46.8–208.1% and 4.4–99.0%, respectively. The higher N recovery was observed with 11.8-12.5 and 5.3-7.7 percentage points by plant or soil, respectively, and lower N loss with 17.8-19.5 percentage points using $^{15}N$ tracing method in the treatment of ORZ compared to CSB. Correspondingly, higher soil $NH_4^+$-N and $NO_3^-$-N contents remained in the root zone when N was applied with ORZ. What's more, although increasing N fertilization generally inhibited nodulation and nitrogenase activity of faba beans, ORZ alleviated this inhibitory effect. The N application with ORZ seemed to be an efficient and promising way on N nutrient management for multi-wins of yield, NUE, economic and environmental benefits.

**Keywords:** One-time root-zone fertilization; N use efficiency; N recovery; Faba bean; Nodulation

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# Soybean rhizospheric carbon metabolism modulated by neighbouring oat through increased isoflavonoids

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**ABSTRACT**

Agroecosystems typified by soybean intercropping reinforce crop interactions with gains in productivity and profound consequence on soils, yet the cascade from metabolites to microbes to functions remains insufficiently resolved. We established controlled rhizobox experiment that contrasted soybean neighboring oat with single soybean, integrating *in situ* zymography and glucose imaging with untargeted metabolomics and metagenomics. Daidzein was tested for its differential induction of distinct carbon substrate decomposition using substrate-induced respiration, as a key rhizosphere metabolite.

With oat as a neighbor, the soybean rhizosphere shows enhanced isoflavonoid and coumarin production and activation of the phenylpropanoid pathway. These metabolites act as selective chemical cues and substrate contexts that jointly enrich and stabilize decomposer oriented bacterial lineages, for example *Flavobacteriales*. Reliance on central carbon metabolism such as the TCA cycle, one carbon metabolism, and gluconeogenesis is attenuated, while the potential for degrading polymeric substrates such as hemicellulose and pectin is increased. Exogenous daidzein provides causal support for this mechanism. It broadly promotes utilization of labile carbon, yet it amplifies decomposition of the recalcitrant substrate arabinogalactan only within the community and metabolic framework created by soybean with an oat neighbor. Daidzein raised soil metabolism of arabinogalactan by 1.2 times only in soybean rhizospheres neighboring oat, with no response in single cultivation. In contrast, glucose induced respiration increased 1.4 times over seven days after daidzein addition under both cultivation regimes.

Taken together, soybean with an oat neighbor reconstructs the rhizosphere metabolite microbe function axis, shifting carbon cycling from a central metabolism dominated regime to one dominated by polymer decomposition and conferring context dependent sensitivity to the specific signal daidzein. These results outline a biochemical route by which crop interactions redirect rhizosphere carbon fluxes and influence short term turnover and long-term soil carbon stability.

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# Contrasting rhizosphere strategies of maize: How drought severity and duration affect root and rhizosphere traits in soils of varying texture

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**ABSTRACT**

A comprehensive understanding of crop strategies for soil resource acquisition is critical for achieving sustainable food security as climate change progresses. Root and rhizosphere traits are central to the acquisition of water and nutrients, yet variety-specific rhizosphere strategies, their plasticity, and their responses to changing water availability remain largely obscure. Here, we investigated root and rhizosphere traits of maize (Zea mays L.) along two contrasting belowground strategies – do-it-yourself vs. outsourcing – and how these strategies respond to drought severity and duration in soils of varying texture. In a controlled greenhouse experiment, six maize varieties previously characterized as do-it-yourself strategists (e.g. by high specific root length, reduced root-derived C input into the rhizosphere) or outsourcing strategists (e.g. by larger root diameter, higher arbuscular mycorrhization, and greater rhizosheath formation) were grown in two contrasting soils (silt loam vs. loamy sand). Plants were exposed to five distinct water availabilities: optimal (1), moderate (2), and low (3) water availability, as well as reciprocal shifts shortly before sampling - dry-down of initially well-watered plants (4) and rewetting of initially drought-stressed plants (5). We quantified root morphology and chemistry, root exudation, arbuscular mycorrhization, rhizosheath properties - including specific rhizosheath mass and microbial biomass carbon (MBC) and nitrogen (MBN) - and integrated these traits using multivariate statistics to identify strategy–environment interactions. Preliminary results showed that soil texture was the dominant factor influencing root morphology and microbial biomass responses under both optimal and low water availability, with stress responses being more pronounced in the sandy soil. Drought led to opposite root trait adaptations depending on soil texture: root diameter increased under drought in sandy but decreased in loamy soil, indicating that the direction of trait plasticity is co-determined by soil physical constraints rather than intrinsic to the plant. A modification of the rhizosphere strategy, particularly of do-it-yourself-strategists in sandy soils and of outsourcing-strategists in loamy soils, can therefore be assumed, but only if sufficient phenotypic plasticity is present at the variety level. Microbial biomass responses were consistent across soils, with drought causing declines in MBN while MBC remained stable. Specific rhizosheath mass was highest in plants exposed to early drought followed by rewetting, especially in sandy soils, and was significantly greater under continuous severe drought than under initially optimal and late severe drought conditions. This pattern suggests that drought severity and duration promote rhizosheath formation, largely independent of soil texture and soil water content at the time of sampling. Our findings highlight the role of soil texture and drought dynamics in determining root and rhizosphere trait combinations and their plasticity in maize, with implications for breeding drought-resilient crops to specific soil environments.

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# Genotype-Specific Rhizosphere Strategies for Phosphorus Acquisition in Tea Plants under Organic Substitution

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**ABSTRACT**

Phosphorus (P) limitation in acid soils leads to high dependency on mineral fertilizers, resulting in low P-use efficiency. Although organic sources offer a sustainable alternative, how their utilization is governed by the interplay between plant genotype and the rhizosphere microbiome remains poorly understood. *Camellia sinensis* is typically grown on acid soils that readily fix phosphorus, and genotypes vary considerably in their phosphorus use traits. We characterized cultivar-specific P acquisition strategies by growing an albino 'Huangjinya' (HJY) and a green-leaf 'Longjing 43' (LJ43) in P-deficient soil under three fertilization treatments: no P (CK), mineral P (Pm), or organic P (Po). A comprehensive dataset was generated, including plant P accumulation, root morphology, soil chemical properties, rhizosphere metabolites, and the microbial community's structure and function, to elucidate genotype-specific acquisition mechanisms.

Organic phosphorus (Po) substitution significantly boosted shoot P accumulation in both tea cultivars relative to the no-P control (CK), with performance comparable or superior to mineral P (Pm) application, while shoot biomass remained consistent across treatments. Under Po amendment, HJY markedly increased the availability of soil P, alongside elevating soil organic carbon and total nitrogen concentration. In contrast, LJ showed a minimal response in soil available P but exhibited a pronounced increase in root length and surface area. Notably, root morphological traits were negatively correlated with shoot P concentration in HJY, a relationship absent in LJ. These divergent responses indicate cultivar-specific P-acquisition strategies: rhizosphere-driven solubilization in HJY versus root proliferation-based exploitation in LJ.

The rhizosphere microbiome was reconfigured by organic P fertilization in a genotype-specific manner. Po fertilization in HJY restructured bacterial and fungal communities, enriching bacterial metabolic pathways for carbohydrate, nucleotide, glycan, and cofactor metabolism. These pathways correlated positively with soil available P (SAP). We identified succinic acid as a key metabolite, specifically elevated by Po in HJY and uniquely correlated with SAP, SOC, and TN. Network analysis indicated greater complexity in HJY, associating the Po-enriched fungus *Rhizopus* and putative P-solubilizing bacteria (e.g., *Arthrobacter, Mesorhizobium, Acidibacter*) with succinic acid and available P. In contrast to HJY, the green-leaf cultivar LJ exhibited stable bacterial functions but enriched fungal guilds (e.g., mycorrhizal and saprotrophic fungi) and the *Burkholderia–Caballeronia–Paraburkholderia* cluster, which correlated with root growth. Our results demonstrate that organic P can effectively substitute for mineral P in tea cultivation, with efficiency governed by distinct genotype-specific rhizosphere processes: a solubility-based strategy in HJY versus a root foraging-based strategy in LJ.

We demonstrate that plant genotype dictates the recruitment of specific rhizosphere consortia, which deploy complementary P-acquisition strategies through functional microbiome-metabolome interactions. This finding challenges the view of universal fertilizer efficacy, showing it is instead co-determined by plant genetics and the microbiome. Thus, integrating host genotype and microbial traits into agriculture is essential for developing precised fertilization strategies that enhance nutrient efficiency and reduce environmental impact.

# Diversified cropping systems with complementary root growth strategies improve crop adaptation to and remediation of hostile soils

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**ABSTRACT**

Hostile soil conditions have a global impact on crop production. While root traits of individual plant species adapted to specific hostile soils are well studied, a comprehensive synthesis of how to use diversified cropping systems with complementary root growth strategies to adapt to and remediate hostile soils is lacking. We begin by providing definitions, categorizations, and global distribution of hostile soils, followed by a synthesis of recent advances in below-ground niche complementarity or facilitative root interactions among crop species in diverse cropping systems across various hostile soils. Lastly, we highlight the significance of cultivating a robust understanding of root adaptations for crop diversification in hostile soils for future research. Diversified cropping systems that incorporate complementary root growth strategies can efficiently utilize nutrients and mitigate abiotic stress in hostile soils, such as nutrient deficiency, aridity, and waterlogging conditions. Furthermore, intercropping hyperaccumulator plants or halophytes with crops is effective in reducing metal or salt accumulation in target crops grown in contaminated or saline-alkali soils, respectively. Cover crops could create biopores for succeeding crop roots in compacted soils, while diversified cropping systems aid in preventing additional soil erosion in eroded areas. Leveraging diverse root traits can also contribute to the suppression of soil-borne diseases and pests within intercropping setups. Enhancing diversified cropping systems necessitates the application of novel methods and technologies for root studies. This multifaceted approach is crucial for sustaining yield under the challenges posed by multiple hostile soil conditions, especially within the context of climate change.

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# Cross-kingdom nutrient exchanges in the plant-arbuscular mycorrhizal fungi-bacteria continuum

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**ABSTRACT**

Mycorrhizal symbioses are pervasive interkingdom interactions established between land plants and soil fungi. Among them, the association between plants and arbuscular mycorrhizal (AM) fungi is well acknowledged for its dramatic impacts on plant performance and ecosystem functioning. Only recently, AM fungi-associated bacteria have been identified as cooperative actors which participate in the two-partner symbiosis; the bacteria which colonize the hyphosphere (the thin soil area surrounding the extraradical hyphae) are named hyphospheric bacteria to distinguish them from bacteria living inside the AM hyphae. We develop the novel concept of plants-AM fungi-bacteria (PAMFB) continuum to summarize the current advances and discuss future perspectives in soil microbiology. First, we describe the top-down carbon flow and the bottom-up mineral (especially phosphorus and nitrogen) flow in the PAMFB continuum as well as how AM fungi-bacteria interaction influences biogeochemical cycling of nutrients (e.g., carbon, phosphorus and nitrogen). Second, we discuss how AM fungi interact with hyphospheric bacteria or endobacteria to regulate the nutrient exchanges between plants and AM fungi, and the possible molecular mechanisms underpinning this continuum. We focus on future perspectives for studies on the hyphosphere to facilitate applications of AM fungi and hyphospheric bacteria in the current context of sustainable agriculture. We present the most recent advances in our understanding of how plants, AM fungi, and their associated bacteria exchange host plant–derived C and soil-derived minerals. These exchanges provide energy to the heterotrophic partners and economically convenient nutrients to plants.

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# Integrating plant–microbial diversity and mixed litter decomposition to enhance nutrient coupling and productivity in intercropping systems

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**ABSTRACT**

Legume-grass intercropping is considered a planting system that improves crop nutrient use efficiency; however, the contribution of returned straw to crop nutrient uptake in such intercropping systems remains unclear. The study employed a field frame experiment to quantify nitrogen utilization rates of maize straw by subsequent crops, traced using $^{15}$N-labeled maize straw incorporated into the soil, and integrated metagenomic sequencing to identify key driving microorganisms. In a field frame experiment, five kinds of straw incorporated into soil treatments were designed: maize straw alone (M), 2:1 mixture of soybean and maize straw (2MS), 1:1 mixture of soybean and maize straw (MS), soybean straw alone (S), and without straw (CN). Each returning patterns were set with three kinds of planting patterns: monocropping maize (M), intercropping maize/soybean (IM/IS), and monocropping soybean (S). Compared with the M treatment, the average utilization rate of maize straw $^{15}$N by maize grains in the MS and 2MS treatments was significantly increased by 1.7 times and 1.2 times, respectively; the MS treatment was significantly increased by 3.7 times in soybean grains. Compared with monocropping, under the M, 2MS, and MS treatments, the average utilization rate of maize straw $^{15}$N by maize grains increased by 100.20%, 82.53% and 74.86% respectively, after intercropping. Compared with other returning patterns, the soil bacteria and fungi diversity in the MS treatment was significantly increased. Furthermore, intercropping significantly increased the abundance of *Rubrobacter* and *Entrophospora* and enhanced the abundance of *glnA* and *GLIL* in the soil. This led to an acceleration of the nitrogen cycling rate in the soil and an increase in the utilization rate of maize straw $^{15}$N by grains. Moreover, intercropping can directly promote denitrification, indirectly promoting nitrogen transport and organic nitrogen metabolism processes, thereby accelerating the inorganic Phosphorus solubilization and organic Phosphorus mineralization, and ultimately accelerating the polyphosphate synthesis. The results indicate that intercropping facilitates the return of combined crop straws, which enhances the combined straw decomposition effect and strengthens the selection and complementarity effects of underground microorganisms. This mechanism effectively promotes crop uptake of returned maize straw, thereby improving soil N-P coupling capacity and maintaining the productivity and stability of the system.

**Keywords:** Soybean/maize intercropping; Straw returning; Microbial diversity; Nitrogen–Phosphorus coupling.

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# Rhizosphere bacterial communities mediate host genetic effects on agronomic traits in soybean

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## ABSTRACT

How plant genotypes shape their rhizosphere microbial communities and jointly influence phenotypes is a core issue in the field of plant-microbe interactions. This study aims to systematically analyze the influence of soybean host genotypes on the structure of rhizosphere bacterial communities and quantify the relative and synergistic contributions of genotypes and microbial communities to key agronomic trait variations. Using 176 soybean varieties as materials, this study employed a strategy combining multi-omics and statistical modeling: 1) Analyzing the correlation between host genetic distance and microbial community Bray-Curtis distance through Mantel test; 2) Calculating the heritability ($H^2$) of bacteria at different taxonomic levels (phylum to genus) to assess host dependence; 3) Constructing linear models based on SNP (Single Nucleotide Polymorphism), based on genetic marker ASV (Amplicon Sequence Variant), and their combination, and evaluating their phenotypic variance explanation rates for traits such as plant height, number of main stem nodes, number of branches, hundred-grain weight, and seed yield per plant through cross-validation. The main results show that host genetic distance is significantly positively correlated with the similarity of rhizosphere bacterial communities (r=0.083, p=0.013). The bacterial heritability shows hierarchical dependence, with the highest at the genus level ($H^2$= 0.452), and core bacterial genera such as *Geodermatophilus* exhibit strong host dependence. The average explanatory rate of the genotype model for five traits is 31.74%, while the average explanatory rate of the rhizosphere genetic marker bacterial model is higher (44.53%). Among them, the bacterial explanation rate for the number of main stem nodes is as high as 69.24%. The combined model of genotype and microbial community has an average explanation rate of 66.64%, which is significantly higher than either of the individual models, indicating a synergistic effect and joint shaping of phenotypes. Through microbial community association analysis, 359 genetic marker ASVs related to traits were identified. Among them, *Pseudomonas* and *Bacillus*, which have high heritability and multi-trait association, were determined as key candidate functional genera. This study demonstrates that host genotypes can specifically recruit rhizosphere bacteria, especially a group of core functional bacteria with high heritability, and interact with these microorganisms, jointly explaining most of the variation in soybean agronomic traits. This provides empirical evidence for the regulatory path from "host genotype→rhizosphere microbial community→plant phenotype" and identifies *Pseudomonas* and *Bacillus* as key targets for subsequent microbial community-assisted breeding and functional validation.

**Key words:** Host genotype, Root-associated bacterial community, Phenotypic variation, Microbiome-assisted breeding

**Genetic variability of root-associated bacteria in different genotypes of soybeans**



**Figure 1. a Bacterial heritability across taxonomic levels. b Top 10 core bacterial genera ranked by heritability.**

Bacterial heritability shows a hierarchical dependence at different taxonomic levels, indicating that the host genotype has limited influence on higher-level communities, but has a significant regulatory effect on specific core bacterial communities. At the phylum level, the heritability of *Acidobacteria* is the highest ($H^2$=0.2409); at the family and genus levels, bacterial communities such as *Geodermatophilaceae* ($H^2$=0.3403) and *Geodermatophilus* ($H^2$=0.452) exhibit strong host dependence, while various known beneficial and stress-resistant functional bacteria such as *Pseudomonas* and *Sphingomonas* also have moderate heritability, suggesting that the host genotype can selectively recruit bacterial groups related to metabolic adaptation, forming a rhizosphere microbial community with genotype characteristics.

**Association patterns between host genotype and rhizosphere bacterial community structure**



**igure 2. Association between host genetic relationships and rhizosphere bacterial genetic patterns**

To investigate the influence of soybean host genotype on rhizosphere microbial community structure, a Mantel test was performed to assess the relationship between host genetic distance and microbial community Bray-Curtis dissimilarity. The results revealed a significant positive correlation between host genetic distance and the Bray-Curtis distance of rhizosphere bacterial communities (r=0.083, p=0.013), indicating that genetically similar soybean cultivars more similar rhizosphere bacterial community compositions. These findings demonstrate that host genotype exerts a significant influence on the structure of rhizosphere bacterial communities.

**Effects of genotype-rhizosphere bacterial community covariation on agronomic traits**



**Figure 3. Contribution of rhizosphere bacteria to phenotypic prediction**

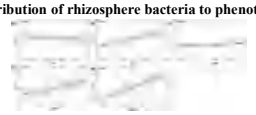


**Figure 4. Simulated effects of genetic and microbiome variation on agronomic traits**

To elucidate the contribution of genetic variation to the formation of key agronomic traits, we first constructed linear regression models to evaluate the effects of host genotype on major growth traits (plant height, number of main stem nodes, and branch number) and yield-related traits (hundred-grain weight and Seed yield per plant) across 176 soybean cultivars. Using thirty rounds of five-fold cross-validation, SNP-based models explained, on average, 31.97%, 24.64%, 57.27%, 34.25%, and 10.59% of the phenotypic variance in plant height, number of main stem nodes, branch number, hundred-grain weight, and single-plant yield in the test sets, respectively (Figure 3).Given that rhizosphere microorganisms have been shown to enhance plant stress tolerance and promote growth and yield formation, we further assessed the contribution of the rhizosphere microbiome to trait variation. Amplicon sequence variants (ASVs) with a prevalence≥90% across all samples and a relative abundance>0 were selected as candidate features to construct rhizosphere bacterial predictive models, which were evaluated using the same thirty rounds of five-fold cross-validation. The results showed that genetically tagged rhizosphere bacteria explained 49.49%, 69.24%, 33.69%, 47.70%, and 22.52% of the phenotypic variance in plant height, number of main stem nodes, branch number, hundred-grain weight and seed yield per plant, respectively. To further disentangle the synergistic effects between host genotype and the rhizosphere bacterial community, candidate SNPs and candidate ASVs were jointly incorporated into linear mixed models to assess their integrated contribution to phenotypic variation. The combined models explained 68.70%, 80.77%, 75.24%, 74.56%, and 33.91% of the phenotypic variance in plant height, number of main stem nodes, branch number, hundred-grain weight, and seed yield per plant, respectively (Figure 4). Overall, the combined genotype-rhizosphere microbiome models significantly outperformed models based on either host genotype or rhizosphere bacteria alone.

**Rhizosphere genetically tagged bacteria associated with soybean agronomic traits**



**Figure 5. The 359 genetically tagged bacteria associated with soybean agronomic traits**

Through microbiome association analysis, a total of 359 genetically tagged ASVs significantly associated with agronomic traits were identified within the bacterial community, predominantly belonging to 11 phyla and 89 genera. The most abundant phyla were *Proteobacteria*, *Actinobacteria*, *Firmicutes*, *Bacteroidetes*, and *Planctomycetes*. Among the highly heritable key genera, *Geodermatophilus* ($H^2$=0.4520), Acidiphilium ($H^2$= 0.2002), *Pseudomonas* ($H^2$=0.1842), *Bacillus* ($H^2$=0.1628), and *Carnobacterium* ($H^2$=0.1563) showed close associations with soybean agronomic traits. Notably, *Pseudomonas* and *Bacillus* were significantly associated with key traits such as plant height and yield. Based on their high heritability, strong trait associations, and potential predictive capacity, *Pseudomonas* and *Bacillus* were selected as core candidate genera for subsequent functional validation.

**Conclusion**

Soybean host genotype significantly shapes rhizosphere bacterial community structure, with host genetic distance positively correlated with bacterial community similarity, indicating a clear host genotype dependency of the rhizosphere microbiome. The host dependency of rhizosphere bacteria exhibits a pronounced hierarchical pattern across taxonomic levels, with the highest heritability observed at the genus level. Core genera such as *Geodermatophilus* display high heritability, suggesting that host genotype primarily influences the rhizosphere microbiome by modulating specific core functional taxa. Host genotype and the rhizosphere microbiome jointly exert a significant synergistic effect on the variation of key soybean agronomic traits, with combined models explaining a substantially higher proportion of phenotypic variance than models based on either factor alone. Notably, *Pseudomonas* and *Bacillus*, characterized by high heritability and multi-trait associations, serve as key functional taxa and act as critical regulatory hubs connecting the “host genotype–rhizosphere microbiome–plant phenotype” pathway.

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# Rhizobiome Partners to Optimize Nutrient Transfers from Soil to Plants

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**ABSTRACT**

Global production of high-yielding, nutritious crops depends upon judicious application of fertilizers to meet crop demands and replenish soil nutrient reserves. Ideally, this approach should maintain soil fertility and food security. In reality, incomplete nutrient use by crops and nutrient loss from soils is responsible for inefficient nutrient cycling in agroecosystems. Here, we discuss the design of closed loop crop systems with an optimized internal nutrient recycling process. The key characteristic of these designed crop systems is high nutrient retention in the plant and soil compartments, which requires an efficient nutrient flux between physicochemical and biological pathways. The physicochemical reactions for nutrient retention involve sorption on reactive soil surfaces, as well as nutrient occlusion and precipitation with soil organo-minerals, including aggregates. On the biological side, the nutrient transfers are mediated by roots and their rhizobiome partners. Roots and their rhizobiome, which include root-associated and endophytic microorganisms, produce and respond to chemical signals. This cross-talk involves the exchange of hundreds of metabolites that alter plant growth, development and nutrient acquisition at the genetic, cellular, physiological and morphological levels. This allows the root-rhizobiome partners to engineer their shared rhizosphere and optimize nutrient transfers for their joint benefit. We will discuss how these fundamental partnerships can inform soil management in designing closed loop crop systems with enhanced nutrient use efficiency.

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# Screening groundnut genotypes for their nutrient efficiency in calcareous soils

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**ABSTRACT**

Soil calcareousness is the major growth limiting factor in many arid and semiarid regions, which naturally limits plant growth and yield due to poor soil organic matter, deficient nutrient availability and high pH. On the other hand, fixation of nutrients in calcareous soils is an inevitable problem that corresponds to very low use efficiency of applied fertilizer nutrients due to various chemical reactions like precipitation, fixation and adsorption (Chitdeshwari&Brindhavani,2023, Rukmani *et al.,* 2023). In this context, evaluating the inherent potentials of the crop genotypes for calcite dissolution potentials and nutrient efficiency is essential to avoid crop loss and to reduce cost of fertiliser inputs.Hence a set of greenhouse screening experiments were conducted with ten groundnut genotypes viz., CO 6, CO 7, TMV 2, TMV 10, TMV 13, TMV 14, VRI 7, VRI 8, ALR 2 & BSR 2 to assess the phosphorus (P), Zinc (Zn) and Iron (Fe) efficiency and their calcite dissolution potentials on calcareous soils having the free $CaCO_3$ content of <5, 5-10, 10-15, 15-20 and > 20%. The experiment was conducted on a factorially completely randomised block design with three replications for 45 days and harvested. The plant growth attributes, dry matter production, nutrient availability, content and uptake were estimated and reported. The nutrient efficiency of genotypes and their calcite dissolution potentials were also computed to screen the tolerant crop varieties suitable for calcareous soils.

Increasing soil calcareousness reduced the growth,dry matter production, nutrient availability, absorption and utilisationwhich varied widely with the groundnut genotypes. Further omission of P, Zn and Fe in the fertiliser schedule considerably reduced the growth attributes of all the groundnut genotypes by 40-50%. Among the ten genotypes tested on five different calcareous soils, the genotype CO 6 recorded higher plant height, root length and SPAD index in both nutrient omitted and supplied pots which was followed by CO7 and TMV 10. Lesser growth attributes were noted with BSR 2 and ALR 2 genotypes indicating their sensitiveness to soil calcareousness. Similar to growth attributes, the dry matter production of the groundnut genotypes also showed greater reduction with increasing soil calcareousness which varied from 18.8 to 43%, 46 to 48 %, 40-50% for skipping P, Zn and Fe respectively. Increasing calcareousness reduced the DMP of all genotypes and the impact was lesser with CO 6 > CO 7 >TMV 10 > TMV 2 > TMV 13 > VRI 8= TMV 14 > VRI 7 > ALR 2 > BSR 2.

Differential behaviour of groundnut genotypes was noticed in absorbing and utilising the applied phosphorus, zinc and iron which decreased with increasing soil calcareousness. Higher nutrient absorption and uptake was noted with CO 6 followed by CO 7 in all the calcareous soils. Lesser nutrient content and uptake was observed with BSR 2, VRI 7 and TMV 13.The greenness index of the genotypes is the indicator of photosynthetic efficiency which decreased markedly with increasing soil calcareousness. Higher greenness index was registered with CO 6 (0.87 to 0.98) and CO 7 (0.85 to 0.93) and the lowest index was observed with BSR2 (0.70 to 0.78). The DMP efficiency was also reduced significantly with increasing soil calcareousness and better efficiency was noticed withCO 7 (76.5 to 80.6%), CO6 (73.2 to 82.1%) and TMV 10 (75.4 to 77.4%). Lesser DMP efficiency was registered in ALR 2 (58.8 to 64.5%) followed by BSR 2 (64.3 to 71.8%).With regard to nutrient absorption and utilisation efficiency by the genotypes, higher P, Zn& Fe absorption and utilisation efficiency was recorded with CO 7 > CO 6 =TMV 10 and the values varied from 75.5 to 89.9%, 75.5 to 89.1% and 73 .3 to 83% respectively. The lowest nutrient absorption and utilisation efficiency was registered with BSR 2 (53.2 to 77%.

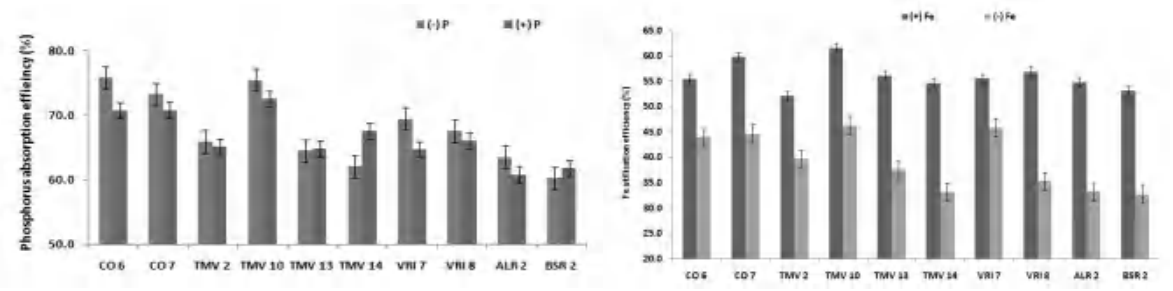



*Fig. 1. Phosphorus absorption and Fe Utilisation efficiency of groundnut genotypes*

To conclude, the groundnut genotypes CO6, CO7, and TMV 10 were found to be efficient in tolerating the soil calcareousness upto 12.5% and possess higher P, Zn, Fe efficiency to grow on calcareous soils which was well correlated with the higher amount of phytosiderophore production, rhizosphere acidification and calcite dissolution hence forwarded for further field studies.

**Key words**: Calcareous soils, groundnut genotypes, nutrient efficiency

**Acknowledgments**

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# AMF modulation of sweet potato plant performance and rhizosphere microecology depends on soil potassium availability: shared and differential strategies

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**ABSTRACT**

Sweet potato, a potassium (K) -favoring crop, strongly relies on arbuscular mycorrhizal fungi (AMF) symbiosis for K nutrition. However, the interactive effects of soil K availability and AMF inoculation on plant performance and rhizosphere microecology of sweet potato remain unclear. We integrated plant growth, nutrient uptake, root exudate metabolomics, and bacterial community profiling to elucidate the regulatory roles of soil K and AMF, and to identified shared and differential strategies under contrasting K levels. Soil K availability dominated rhizosphere microecology remodeling, enriched Chloroflexi, Methylomirabilota, Desulfobacterota, Latescibacterota, Nitrospirota, MBNT15, and NB1j involved in carbon, nitrogen, and sulfur cycling, and simultaneously upregulated signal transduction, primary and secondary metabolic pathways, thereby enhancing root growth and defense capacity. Whereas, AMF fine-tuned rhizosphere microecology and played a central role in improving root growth and nitrogen, phosphorus, and K uptake of sweet potato. In low-K soil, AMF primarily enhanced root growth and nutrient uptake (especially more K uptake), supporting plant adaptation to low-K condition and enriching beneficial microbes like *Haliangium*. Conversely, in high-K soil, AMF further promoted whole plant growth and nutrient uptake (especially more P uptake), while modulating root exudates to optimize resource allocation. Across both K levels, AMF consistently activated auxin biosynthesis, and enriched Planctomycetota via root exudates (indole-2-carboxylic acid, L-arabitol, tropic acid), thereby promoting root growth and nutrient uptake. AMF-mediated adaptation exhibited soil K-dependent plasticity, adopting stress adaptation in low-K and growth optimization in high-K soils. By integrating nutrient uptake, metabolic reprogramming, and microbial enrichment, AMF improved sweet potato adaptability and performance, providing a theoretical basis for AMF inoculation combined with targeted K management.

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# Drivers of Potassium Efficiency in Sweet Potato: Genotypic Variation, Partitioning Dynamics, and AMF-Mediated Rhizosphere Optimization

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**ABSTRACT**

Significant intraspecific variation exists among sweet potato genotypes in potassium (K) uptake, utilization efficiency (KIUE), and growth response to varying K supplies. Field screening identified genotypes such as Xu28 and Wan5 as K-efficient genotypes, and Ji22 as K-inefficient genotype. K-efficient genotypes demonstrate superior K accumulation dynamics, characterized by peak uptake during early growth stages under deficiency and effective partitioning and redistribution of K at maturity, leading to higher root: shoot K ratios and reduced K concentration in roots at harvest. KIUE is negatively correlated with whole-plant K concentration but positively linked to the K harvest index and relative root growth from the expanding stage to maturity, rather than directly with total root dry matter yield. The interaction between K availability and arbuscular mycorrhizal fungi (AMF) critically modulates root morphology, nutrient uptake, and plant performance. AMF inoculation, particularly with *Claroideoglomus etunicatum*, synergizes with K application to optimize root architecture (e.g., increasing root tip number, length, and surface area) in high-KIUE genotypes like Xu28. This synergy enhances dry matter allocation to roots and promotes root K accumulation while limiting excessive aboveground K allocation. Soil K availability dictates rhizosphere microecology remodeling, enriching microbial taxa involved in nutrient cycling. AMF further fine-tunes this environment, enhancing plant adaptation to low-K stress by boosting K uptake and enriching beneficial microbes (e.g., *Haliangium*), while under high-K conditions, AMF prioritizes phosphorus uptake and growth optimization. Consistently, AMF activates auxin biosynthesis and enriches phyla like Planctomycetota via specific root exudates, promoting root development and nutrient acquisition across K regimes. In conclusion, achieving high K-use efficiency in sweet potato involves a complex interplay of genotypic selection for optimal K partitioning and redistribution, coupled with strategic AMF inoculation that tailors root morphology and rhizosphere microbial communities in a K-dependent manner. This integrated approach provides a theoretical foundation for improving sweet potato cultivation through genotype selection and synergistic nutrient-microbe management.

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# Mycorrhizal solubilization of phosphate rock increases arsenic accumulation in Pteris vittata: Trade-off root strategies and dual P-transporter pathways

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## ABSTRACT

Being a raw material for P-fertilizers, insoluble phosphate rock (PR) is less available for plants, unless with arbuscular mycorrhizal (AM) helpers. This also occurs in arsenic (As) hyperaccumulator *Pteris vittata*, yet the underlying mechanisms behind mycorrhizal P acquisition and As accumulation remain unclear. Using PR as the sole P source and *Rhizophagus irregularis* inoculation in a sand-culture system, As exposure at 10 and 100 μM accentuated mycorrhizal colonization and responsiveness of growth and P uptake compared to no-As control. We further investigated mycorrhizal associated trade-offs and P-transporter expressions in *P. vittata* symbiont after growing for 60-day in a contaminated soil containing 75 mg $kg^{-1}$ As, and 1% mass ratio of AM inoculum and/or PR addition. Compared to the PR-alone addition, *P. vittata* biomass and frond P content were rose by 15−26%, while As accumulation in the fronds was increased by 70% to 1190 mg $kg^{-1}$ in the AM+PR treatment. Following lower allocation of root biomass and exudation (6−8%), mycorrhizal *P. vittata* probably activated a scavenging strategy in P and As acquisition, resulting in their 15−29% depletion of available contents in the rhizosphere. As evidences, AM symbiosis upregulated inherent *PvPht1;3* by 2.0-folds in *P. vittata* roots. Whereas PR enhanced gene expressions of *RiPT1* in AM fungi (2.7-folds) and *PvPht1;6* in *P. vittata* symbiont (2.2-folds), corresponding to the 15% greater hyphal density in the AM+PR compared to AM treatment. By linking mycorrhizal traits to *P. vittata* uptake of P and As, this study provides valuable strategies for As-phytoremediation.

**Keywords:** *Rhizophagus irregularis*, mycorrhizal responsiveness, AM colonization and hyphal density, root biomass and exudation, inherent *PvPht1;3* and symbiotic *PvPht1;6* P-transporters

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# Bioprospecting soil bacteria to increase sulfate release from elemental sulfur in tropical soil

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**ABSTRACT**

Given the increasing sulfur (S) deficiency in tropical soils, mainly due to reduced atmospheric deposition and the growing use of S-free fertilizers, and considering that soil S cycling is largely mediated by specialized microorganisms, it is necessary to investigate microbial strategies that improve S availability to plants. Thus, we aimed the isolation, characterization and selection of bacterial strains able to oxidize elemental sulfur (ES) and make it available in soil as sulfate ($SO_4^{-2}$,). First, eight soil with different residual concentration of S were sampled and incubated for 15 days to enrichment of S-oxidizing strain in a sodium thiosulfate medium. From 44 obtained isolates, four high-performing strains were selected and identified as belonging to the genus *Thiomonas* based on 16S rRNA gene sequencing. After, a destructive soil incubation experiment was conducted in a completely randomized design arranged as a 6 × 4 factorial (treatment × time), with four replicates per combination (n = 96). Treatments were: control without $S^0$ (C), $S^0$ without inoculation ($S^0$), and $S^0$ inoculated with strains S02B1-R3 (T1), S01B5-R1 (T2), S01B1-R3 (T3), or S01B4-R2 (T4). Elemental S was applied at 3 mg $kg^{-1}$ to a dystrophic Oxisol (medium texture, low fertility). A common baseline at day 0 was obtained from the characterization of the soil used. Samples were collected at 10, 20, 40 and 60 days, and sulfate was extracted with calcium phosphate and quantified as $SO_4^{-2}$ (mg $kg^{-1}$). Were observed that sulfate accumulation was affected by treatment, time and their interaction, evidencing time-dependent inoculant effects. The control remained at background levels throughout. $S^0$ showed progressive $SO_4^{-2}$ accumulation, confirming basal oxidation. Inoculation enhanced ES oxidation in specific windows: at 10 days, T2 and T4 produced significantly more sulfate than $S^0$; at 20 days, T2 exceeded $S^0$; at 40 days, T1 and T4 exceeded $S^0$. By 60 days, T1 oxidized about two times more ES than the non-inoculated $S^0$ treatment, indicating a clear increase in the oxidation rate. Overall, bacterial inoculation can accelerate ES oxidation, but performance is strongly time-dependent, while demonstrating that selected bacterial strains can increase the oxidation rate of ES, making them a sustainable alternative for supplying S to crops.

**Keywords:** Microbial inoculant, sulfur oxidation rate, nutrient cycling, sustainable fertilization.

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# Nitrogen form-induced spatiotemporal coupling of root growth and phosphorus uptake

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## ABSTRACT

**Background**
Rhizosphere pH is a key determinant of soil phosphorus (P) availability. However, how different nitrogen (N) forms shape the root-segment-specific rhizosphere pH over space and time, and thereby regulate P mobilization and uptake along growing roots remains poorly understood.
**Objectives**
This study aimed to elucidate how N forms regulate pH dynamics in the rhizosphere and to clarify the mechanisms by which these rhizosphere pH influence P mobilization and root P acquisition.
**Methods**
Non-invasive micro-test technology (NMT) and diffusion gradient technique in thin films (DGT) were combined in hydroponics and rhizo-box experiments to quantify rhizosphere pH regulation by different N forms and its contribution to the activation and uptake of distinct P sources.
Experiment 1 (Hydroponics):
Ion fluxes of maize roots were measured using NMT, and P uptake rates of root segments were quantified with a collection device under three N treatments: ammonium (A), ammonium–nitrate mixture (AN), and nitrate (N).
Experiment 2 (rhizo-box):
A factorial design combining two N forms (A and AN) and three P treatments (no P, $KH_2PO_4$, and sodium phytate) was used to visualize root-segment-specific P mobilization using DGT imaging.
**Results**
Distinct root-segment-specific pH microenvironments developed under different N forms. Ammonium nutrition induced pronounced acidification at the root apex-up to 0.4 pH units lower than basal root regions (Fig. 1). DGT imaging showed strong spatial heterogeneous in P mobilization along the root apex. Among treatments, A+KDP markedly enhanced single-root DGT-P flux, increasing it by 1.1-35.4 fold relative to other treatments (Fig. 2).

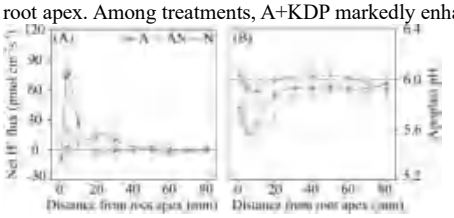


**Fig. 1** $H^+$ flux and apoplast pH in different root segments. Positive on the y-axis = net outflow; negative = net inflow.

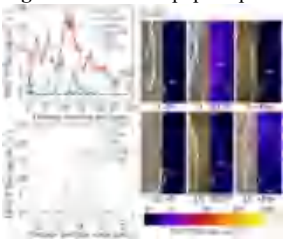


**Fig. 2** Rhizosphere DGT-P fluxes. White arrows mark the positions of transverse line scans; longitudinal profiles extend from the arrow to 30 mm.

**Conclusions**
Ammonium-induced $H^+$ release led to strong acidification at the root apex, yet maximal P uptake occurred in basal root regions characterized by moderate acidification rather than extreme pH reduction. These findings demonstrate that N form regulates P acquisition not simply through rhizosphere acidification, but via the root-segment-specific rhizosphere pH that differentially control P mobilization and uptake. (Fig. 3).

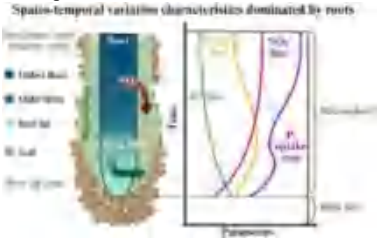


**Fig. 3** Conceptual model. Red arrow represents zones with higher $NO_3^-$ release compared to other root segments; green arrow: higher $H^+$ and $NH_4^+$ release.

**Acknowledgments**
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# Nitrogen use efficiency of intercropping and its drivers: a global meta-analysis

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**ABSTRACT**

Intercropping, as a classic sustainable agricultural practice, has attracted widespread attention for its potential to improve nitrogen use efficiency (NUE) and crop productivity. However, a comprehensive and mechanistic understanding of the underlying N acquisition and allocation processes and its drivers in intercropping remain poorly quantified at the global scale. Here, we conducted a global meta-analysis by synthesizing 786 data records from 97 peer-reviewed studies related to N dynamics in intercrops and showed that intercropping globally accumulated an additional 25.55 ~ 39.37 kg N·ha$^{-1}$, while reducing land requirement by 22.48% ~ 23.31% for equivalent N uptake compared with sole crops. The additional N uptake can be amplified by adopting maize/legume strip intercropping, increasing N input and raising planting density. Intercropping did not lower the N harvest index and N concentration of species in intercropping compared to sole cropping, indicating all extra acquired N was channeled into biomass and yield gains without decreasing the grain quality. Our findings confirm that intercropping is a sustainable agricultural practice for safeguarding food security and increasing NUE without compromising yield quality, particularly in maize/legume strip intercropping systems under optimized N input and planting density regimes.

**Keywords:** Intercropping; Nitrogen use efficiency; Nitrogen concentration; Nitrogen harvest index; Drivers

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# Mild to moderate drought stress reinforces the role of functional microbiome in promoting growth of a dominant forage species (Neopallasia pectinata) in desert steppe

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**ABSTRACT**

Desert steppe ecosystems are prone to drought stress, which influences the ecological balance and sustainable development of grasslands. In addition to directly restrict plant growth, drought stress indirectly impacts plant fitness by altering the diversity and function of root-associated microbiomes. This begs the question of whether the functional microbiome of forage plants, represented by synthetic microbial communities (SynComs), can be leveraged to mitigate drought stress in desert steppes and promote the ecological restoration of these fragile ecosystems. A pot experiment was conducted to evaluate the role of SynComs in improving the plant growth and drought stress resistance of *Neopallasia pectinata* (Palt.) Poljak in desert steppe in Inner Mongolia, China. Six SynComs were derived from the rhizosphere and root endosphere of 12 dominant forage species in the desert steppe. Each SynCom comprised two to three bacterial genera (*Bacillus*, *Protomicromonospora*, and *Streptomyces*). We examined the capacities of different SynComs for nutrient solubilization, phytohormone secretion, and enzymatic activity. Under no water stress (75% soil water holding capacity, WHC), single strains performed better than SynComs in promoting plant growth in terms of stem diameter, root length, and plant dry weight, with the greatest effects observed for *Streptomyces coeruleorubidus* ATCC 13740 ($P<0.05$). However, under mild to moderate drought stress (55% and 35% WHC), SynComs outperformed single strains in enhancing plant biomass accumulation and inducing the production of resistance-related substances ($P<0.05$). No significant effect of single strains and SynComs emerged under extreme drought stress (20% WHC). This study underscores the potential of SynComs in facilitating forage plants to combat drought stress in the desert steppe. Mild to moderate drought stress stimulates SynComs to benefit the growth of *N. pectinata* plants, despite a soil moisture threshold (21% WHC) exists for the microbial effect. The use of SynComs provides a promising strategy for the ecological restoration and sustainable utilization of desert steppes by manipulating the functional microbiome of forage plants.

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# Instant organic carbon addition increasing the soil phosphorus availability in calcareous soil

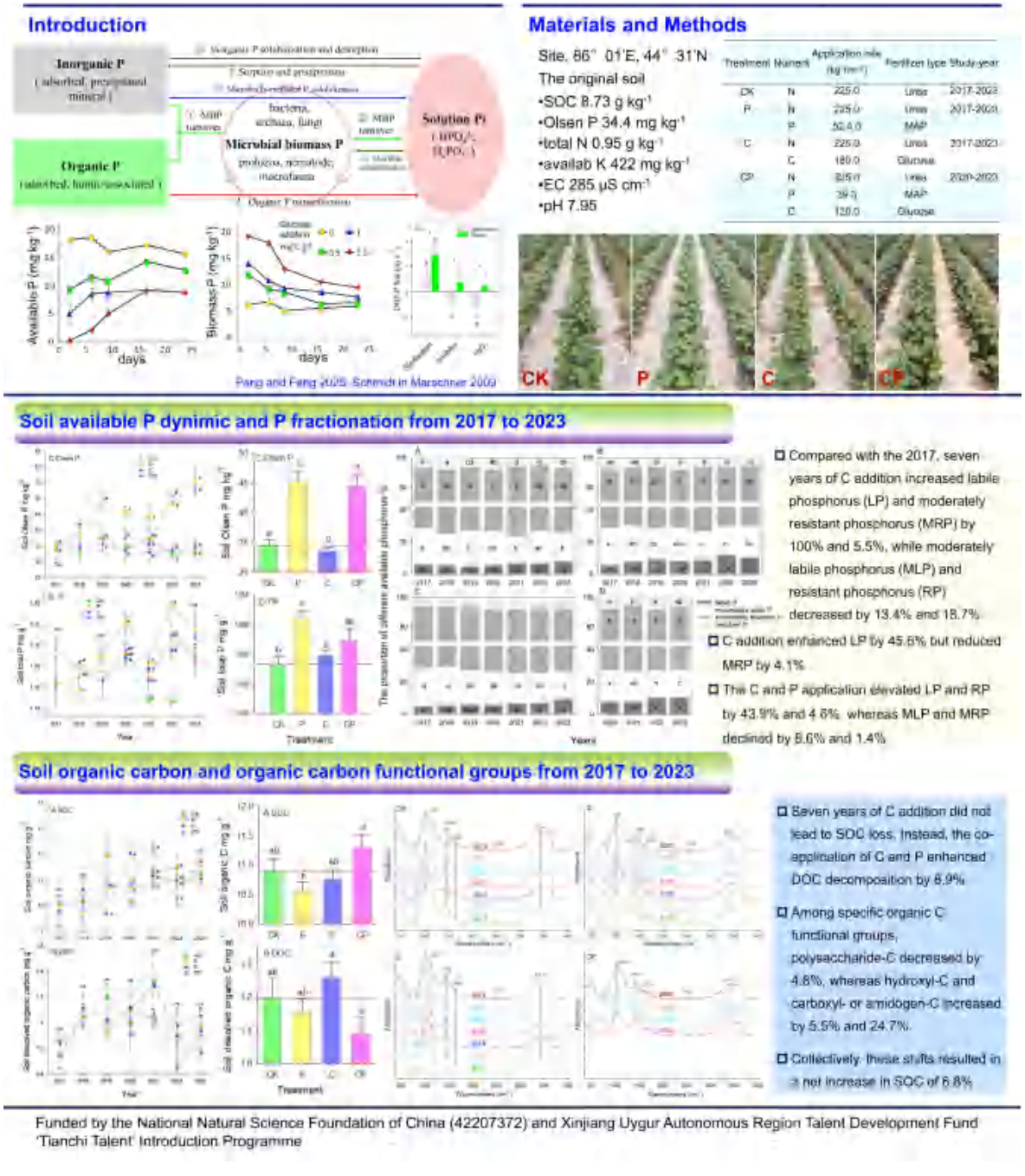
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## ABSTRACT




Funded by the National Natural Science Foundation of China (42207372) and Xinjiang Uygur Autonomous Region Talent Development Fund 'Tianchi Talent' Introduction Programme

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# Soil C:P stoichiometry regulating microbial-mediated phosphorus turnover fluxes in calcareous soil

**Yi Peng[1,2], Gu Feng[2*]**

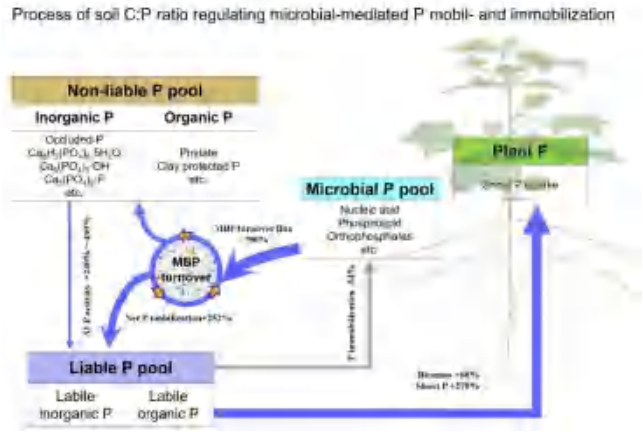
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**ABSTRACT**

Microbial-mediated soil phosphorus (P) mobilization and immobilization processes directly and strongly influence the soil available P pool and plant P uptake. A quantitative description of the microbial-mediated soil P mobilization or immobilization driven by soil carbon (C):P stoichiometry change is a critical task in soil science. We hypothesis that microbial-mediated P mobilization and immobilization will decrease but microbial biomass P (MBP) turnover will increase as soil C:P ratio decreases. In this study, we verified the quantitative relationship between soil C:P ratio and microbial-mediated P mobilization, immobilization, and MBP turnover fluxes by a $^{32}$P-labelling experiment with decreased soil C:P ratio gradients. The results showed that microbial-mediated gross P immobilization was reduced by 54% with decreasing soil C:P ratio, while gross and net P mobilization and MBP turnover were increased by 141%, 252%, and 790%. We verified that declines in the soil C:P ratio decreased microbial-mediated gross P immobilization but increased gross and net P mobilization and subsequently enhanced P bioavailability. Our results provided an ecological intensification opportunity by which soil microbial activity and P fluxes can be quantitatively manipulated by altering the C:P ratio in calcareous soil.




**Acknowledgments**

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# Nutrient Management and $N_2O$ Emissions from Agricultural Peatlands in Ireland

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## ABSTRACT

Drained peatlands used for agriculture are hotspots of nitrous oxide ($N_2O$) emissions, yet national greenhouse gas inventories often rely on default IPCC emission factors (EFs), which carry large uncertainties. In Ireland, where over 95 % of its ~20 % peatland cover has been degraded, there is a critical need for country-specific EFs to improve reporting accuracy and inform mitigation strategies. This study aims to quantify the impact of nitrogen (N) inputs and water table depth (WTD) on $N_2O$ fluxes from managed grasslands on peat soil, and to derive Irish-specific Tier 2 EFs.

The aim of this study was to assess the impact of agricultural management practices including N amendment and WTD management on $N_2O$ emission from agricultural grass-based peat soil and to contribute to the derivation of Irish-specific Tier 2 EFs. The experiment was conducted at two different peat soil sites on grassland in the Irish midlands (TB and CR). Each site included plots with contrasting water regimes (a drier and a wetter side) to represent different WTD conditions. Four treatments were applied to the soil in a fully randomized block design: control (C), calcium ammonium nitrate (CAN) fertilizer, sheep urine (SU), and cattle urine (CU). The C and CAN treatments were applied in spring, while SU and CU treatments were applied across three growing seasons. $N_2O$ fluxes were monitored continuously for three months post-application using automated chambers, with year-round monitoring on control plots. Key site-specific characteristics that drive GHG production were also monitored to serve as proxies for emissions.

Average $N_2O$ EFs ranged from 0.07% to 5.36% across all treatments and sites. While EFs were consistent across application seasons, they differed significantly between sites, underscoring the importance of site-specific conditions. Notably, EFs from urine treatments were generally lower than IPCC Tier 1 defaults (0.77% for cattle urine, 0.39% for sheep urine). A critical exception was the wetter area of the CR site, where EFs surged to 2.11–5.36%. At this location, substantial emission peaks were not only observed immediately after N application, but also during rainfall events up to two months later. This suggests that rewetted conditions, coupled with residual N, can create hot moments for $N_2O$ production, potentially via enhanced denitrification during fluctuating water tables. Our findings demonstrate that the hydrology and nutrient status of agricultural peatlands are key determinants of $N_2O$ emissions. The findings will also contribute to the development of nutrient management strategies that balance agricultural productivity with ecosystem functionality.

**Acknowledgments**

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# Enhancing soil phosphorus activation and microbial phosphorus cycling via increasing soil moisture stability in maize production

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**ABSTRACT**

Soil phosphorus (P) activation is a global challenge and crucial for sustainable agricultural production. The coupling between water and P has been widely studied, while the response of soil P cycling to temporal variability of soil moisture and the potential biotic and abiotic mechanisms involved are largely unknown, which limits our understanding of strategies to regulate soil P availability and boost crop yield via water management. We combined metagenomics with sequential P fractionation to explore soil P cycling traits and P availability across moisture regimes with differing temporal variability. Reduced soil moisture temporal variability increased labile P but decreased moderately labile P. This shift was driven by transformations in microbial community structure and function. Lower soil moisture variability increased the abundance of P-solubilizing genes (e.g., *gcd*, *ppk*, *ppx*, *phoA*, *phoD*, and *phy*) and enriched beneficial bacterial genera such as *Sinorhizobium*, *Sphingobium*, and *Arthrobacter*. Specifically, stable soil moisture enhanced soil phosphatase activity by regulating microbial P cycling, thereby significantly promoting the conversion of organic P into available forms. Among these, the *phoA* gene and *Sinorhizobium* were identified as key predictors of labile inorganic P (Pi) during organic P mineralization. Concurrently, the increase in soil labile Pi significantly improved plant productivity and P uptake. In conclusion, this study reveals that a soil moisture stabilization strategy effectively enhances soil P availability and crop productivity, offering a pathway toward eco-friendly and sustainable P management.

**Acknowledgments**

This research was supported by the National Key Research and Development Program of China (2018YFE0112300), the Third Xinjiang Scientific Expedition Program (2021xjkk0200), and the Agricultural Science and Technology Innovation Program.

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# Phosphate rock and microorganisms as a sustainable alternative to soluble P fertilizers in tropical soil

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**ABSTRACT**

The increasing demand for phosphate fertilizers in tropical agricultural systems, coupled with the global dependence on finite and externally sourced inputs, underscores the need to explore alternative phosphorus (P) sources for cultivated soils. In this context, the application of phosphate rock (PR), particularly when combined with phosphate-solubilizing microorganisms, may offer a sustainable alternative to improve P dynamics in soil–plant systems. However, the actual effectiveness of phosphate rocks and phosphate-solubilizing microorganisms in releasing P and matching the efficiency of soluble fertilizers remains poorly understood under tropical conditions. This study aimed to assess the efficiency of different P sources and the use of PSM associated with PR in improving soil P availability and maize growth. A greenhouse experiment was conducted using 5 kg pots filled with an Oxisol and supplied with 50 mg P $kg^{-1}$ of soil. Maize plants (B2782PWU) were cultivated in a completely randomized design with four replicates and nine treatments: Control (no P), Bayovar PR alone or combined with Probiom, Blindagem T, Biofree, or Biotrinsic Simplex, Bayóvar PR + phosphogypsum, single superphosphate (SSP), and triple superphosphate (TSP). Plant growth was evaluated through biometric measurements (height, stem diameter, and number of leaves) and by determining shoot and root dry matter. Nutrient accumulation in the shoot was quantified after acid digestion of plant tissue. Following harvest, soil samples were analyzed for pH, available and total P contents, and acid phosphatase activity to assess P dynamics and soil biochemical responses. At 35 days after emergence, all the P sources and microbial inoculations showed distinct effects on maize growth and soil P status. Phosphate rocks promoted maize growth comparable to soluble sources, although biomass accumulation was generally higher under TSP. The Bayovar PR showed the best agronomic response, particularly when combined with Biotrinsic Simplex, achieving shoot dry matter and P accumulation similar to SSP. All P sources increased soil available and total P relative to the control, but with Bayovar PR treatments reaching levels close to SSP and TSP. These findings indicate that, although the phosphate rock remain less efficient than soluble fertilizers in the short term, Bayovar PR demonstrated higher reactivity and greater potential for use in sustainable fertilization strategies. Future studies should focus on longer-term and field-scale assessments to clarify the residual and microbial effects on P release from phosphate rocks. Because these sources dissolve gradually, they may become more effective over time, supplying nutrients in synchrony with crop demand and contributing to sustained soil fertility. Understanding these processes is essential to confirm their agronomic efficiency and environmental advantages compared with soluble fertilizers in tropical soils.

**Keywords:** Phosphorus availability**,** Nutrient cycling, Microbial-assisted phosphorus recovery, Bayovar

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# Phosphorus mineralization potentials of some soil amendments applied to degraded tropical Ultisol

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**ABSTRACT**

Information on phosphorus (P) mineralization pattern of soil amendments is germane for proper P fertilizer management. This study was conducted to determine the phosphorus mineralization potentials of some soil amendments applied to degraded tropical Ultisol. The experiment was a 4 × 10 factorial experimental set-up fitted in a Completely Randomized Design. Treatments were soil amendments (Control, poultry manure, biosolids, and biochar) and period of incubation (0, 10, 20, 30, 40, 50, 60, 70, 80, 90 days after incubation (DAI)).The properties of both the soil amendments and the experimental soil were determined prior to the incubation experiment. Soil samples were treated with these amendments equivalent to 60 kg P ha-$^{1}$ under field capacity moisture condition and incubated for a period of 90 days. During the incubation period, soil sample was collected at 10 day interval for determination of available P. Results obtained were subjected to analysis of variance and means separated using LSD at 5% level of probability. Also, simple linear correlation analysis was employed to determine relationship between P mineralization and selected soil properties. Results showed that P mineralization varied significantly across the days of incubation and among the soil amendments. In the control soil, available P increased gradually from 10.5 to 25.8 mg kg-$^{1}$ (0 - 70 DAI), then slightly declined to 24.6 mg kg$^{-1}$ at 90 DAI. In contrast, poultry manure amended soil showed rapid rise in available P (42.8 to 67.2 mg kg$^{-1}$) from 0 – 60 DAI, then declined to 58.3 mg kg$^{-1}$ at 90 DAI whereas in biosolids amended soil, steady increase from 14.2 to 41.9 mg kg$^{-1}$ (0 – 80 DAI), stabilizing to 40.5 mg kg$^{-1}$ at 90 DAI. However, in biochar amended soil, there was continuous increase in available P (27.5 – 59.2 mg kg$^{-1}$) throughout the 90 day incubation period, indicating ability of the amendment to support long-term P supply. Results also indicated strong relationship between P availability and soil pH as well as exchangeable calcium. Conclusively, application of the soil amendments 40 - 60 days before planting is germane for optimal P availability in the acidic Ultisol.

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# Biotechnological Strategies to Enhance Phosphorus Use Efficiency in Soybean/Maize Cropping Systems

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**ABSTRACT**

The limited availability of phosphorus (P) in agricultural soils, coupled with the global dependence on highly soluble mineral fertilizers, represents one of the main constraints to food security and sustainable agricultural production. Moreover, a significant portion of the applied P rapidly becomes unavailable to plants, reducing phosphorus use efficiency (PUE). In this context, the combined use of low-solubility phosphate rocks and P-solubilizing microorganisms has emerged as a promising strategy to enhance PUE and decrease dependence on soluble fertilizers. This study evaluated the ability of P-solubilizing microorganisms to mobilize P from phosphate rock to improve PUE and crop productivity in a soybean/maize succession system established on an Oxisol in Mato Grosso, Brazil. The experiment followed a randomized block design with seven treatments and four replications: T1: control; T2: 268 kg ha$^{-1}$ Bayovar (BY); T3: BY + 0.2 L ha$^{-1}$ BiomaPhos; T4: BY + 0.4 L ha$^{-1}$ Phos UP; T5: BY + 0.4 L ha$^{-1}$ Meli-X Turbo; T6: 444 kg ha$^{-1}$ SSP; and T7: 154 kg ha$^{-1}$ MAP. P was applied at soybean sowing and topdressed in maize, while inoculants were applied five days after emergence (DAE). Plant height, stem diameter, number of leaves, grain yield, thousand-grain weight, leaf nutrient contents, and soil chemical attributes were evaluated. Soybean yield showed no statistical differences between BY and soluble P sources, regardless of microbial inoculation. At 30 DAE, BY treatments promoted plant growth and yields comparable to those obtained with soluble sources. Other growth parameters (plant height, stem diameter, number of leaves, and leaf nutrient contents) were not significantly affected by treatments. In maize, no significant yield differences were observed, although P treatments tended to outperform the control. Leaf P concentrations did not differ among treatments. All P sources increased soil available and total P contents compared with the control, with BY + Meli-X Turbo and SSP showing the highest mean values. Soil pH and exchangeable cations (Ca, Mg, and K) were also influenced, with soluble sources and BY combined with microorganisms generally showing better results than the control. Overall, the results indicate that low-solubility phosphate rocks associated with P-solubilizing microorganisms can enhance soil P availability and sustain yields comparable to soluble fertilizers. However, application methods, residual effects, and crop-specific P uptake dynamics likely influenced the responses, highlighting the importance of long-term studies under different production systems.

**Keywords:** Biological P mobilization, Sustainable nutrient management, Microbial-assisted phosphorus recovery

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# Rainfall thresholds and scale-dependent hydrological dynamics of phosphorus speciation in nested purple soil catchments

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## ABSTRACT

Effective governance of agricultural phosphorus (P) non-point source pollution is undermined by episodic, high-magnitude export events, yet the quantitative thresholds triggering these shifts and their scale-dependent transport pathways remain poorly understood (Gao et al., 2014; Khan et al., 2025; Sun et al., 2026). Approaches to optimizing P management must account for how transport mechanisms and ecosystem functionality vary with catchment scale (Chen et al., 2025). This study investigated P export dynamics across four nested catchments (3.2–1236 ha) in a representative agricultural headwater catchment in the purple soil region of the Sichuan Basin, China (Wang et al., 2016). Employing high-frequency automated sampling during storm events (18.2–134 mm) and partial least squares structural equation modeling (PLS-SEM), this study quantified dynamic changes in P speciation. Results revealed a strong nonlinear P export relationship defined by a critical rainfall threshold of 30–50 mm. Below this threshold, export was transport-limited and primarily governed by hydrological leaching, with dissolved total P (DTP) as the dominant fraction. Above it, the system shifted to a detachment-limited regime where pollutant loads increased exponentially driven by erosion, with particulate P (PP) comprising > 95% of the total P load and exhibiting a pronounced first flush effect. This response was highly scale-dependent: small catchments (3.2 ha) showed rapid, slope-dominated responses tightly coupled with rainfall peaks, while larger catchments (> 100 ha) exhibited buffered, delayed hydrographs due to channel network processes (Liu et al., 2017). Critically, this scale-dependent transit altered biogeochemical functionality, as the proportion of bioavailable $PO_4$-P relative to DTP systematically increased with catchment size, attributed to the mineralization of dissolved organic P (DOP) induced by longer hydrological residence times. This work provides the scientific basis for shifting from traditional load-based strategies to spatio-temporal interventions, targeting erosion control in key source areas before critical rainfall thresholds are exceeded.

**Keywords:** Phosphorus speciation; Catchment scale; Rainfall threshold; Transport; Hydrological dynamics

**Acknowledgments**

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# Phosphorus supply intensity and neighboring alfalfa: effects on maize growth, phosphorus uptake, and interaction intensity

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**ABSTRACT**

Phosphorus (P) is a critical nutrient limiting farmland productivity and crop growth. Low phosphate fertilizer use efficiency, coupled with excessive P accumulation in soils, has become an urgent issue to address in agricultural production across China. Moving away from the traditional agricultural model characterized by heavy reliance on high phosphate fertilizer inputs and fully harnessing the inherent potential of plants for efficient P acquisition constitutes a new direction in modern agricultural development.

Root morphology and physiological traits of plants are regulated by neighboring plants. To explore the responses of the gramineous crop maize to neighboring crops (maize or alfalfa ) under varying soil P supply intensities, this study used maize as the target crop and established three planting regimes: Maize was grown alone (single maize) or with maize (maize/maize) or alfalfa (maize/alfalfa). A pot experiment was performed under six distinct soil P supply levels to assess the effects of different neighboring crops on the growth, P uptake, root morphology, and rhizosphere processes of the target maize.

The results demonstrated that under low P (P0, P50) and medium P (P100, P200) conditions, neighboring alfalfa significantly increased the aboveground biomass and P content of the target maize by improving its root morphology and rhizosphere environment, there by exerting a positive promotional effect. Alfalfa exhibited strong responses in both root morphological traits and rhizosphere physiological processes, whereas neighboring maize had no significant impact. In the maize/alfalfa intercropping system, maize promoted the rhizosphere processes of neighboring alfalfa, and root-rhizosphere interactions between maize and alfalfa enhanced soil P availability. This finding highlights that interactions between maize and alfalfa are pivotal for improving soil P use efficiency and productivity in intercropping systems.

# The Art of Breeding Microbial Communities: Unlocking Soil Phosphorus through Artificial Selection

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**ABSTRACT**

Microbial communities, acting as key drivers of ecosystem processes, harbour immense potential for sustainable agriculture practices. Phosphate-solubilising microorganisms, for example, can partially replace conventional phosphate fertilisers, which rely on finite resources. However, understanding the mechanisms and engineering efficient communities poses a significant challenge. In this study, we employ two artificial selection methods, environmental perturbation, and propagation, to construct phosphate-solubilising microbial communities. To assess trait transferability, we investigate the community performance in different media and a hydroponic system with *Chrysanthemum indicum*. Our findings reveal a distinct subset of phosphate-solubilising bacteria primarily dominated by *Klebsiella* and Enterobacterales. The propagated communities consistently demonstrate elevated levels of phosphate solubilisation, surpassing the starting soil community by 24.2% in activity. The increased activity of propagated communities remains consistent upon introduction into the hydroponic system. Additionally, we demonstrate that the propagation approach is reproducible and also effective when applied to recycled phosphate compounds, including struvite and vivianite. Together, our work demonstrates that propagation-based artificial selection can reliably enhance microbial communities to solubilize phosphorus from a wide range of sources, opening new opportunities for sustainable phosphorus management.

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# Phosphorus availability and legacy in highly weathered soils: unveiling the interplay with soil aggregation across diverse agricultural land uses as integrated systems

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**ABSTRACT**

Phosphorus (P) availability is a critical concern in tropical agriculture, particularly in highly weathered Oxisols. Because soil functions are governed by hierarchical and self-organising structures, land use affects P availability and legacy through changes in soil aggregation. However, the impact of integrated agricultural systems (IAS) on P cycling at the aggregate scale remains unclear. Therefore, the objective of this study was to evaluate the relationships between P lability and soil structural parameters—water-stable aggregates (WSA; large, macro, and micro), aggregate stability (AS), and maximum Padsorption capacity (Qmax)—in three Oxisols of contrasting textures under long-term land uses: Integrated Crop–Livestock–Forest (ICLF), Integrated Livestock–Forest (ILF), Integrated Crop–Livestock (ICL), No-Tillage (NT), Conventional Tillage (CT), Rotational Grazing (RG), Extensive Grazing (EG), Permanent Pasture (RP), and Native Vegetation (NV).

At the clayey Site 1, IAS (ICL, ILF, ICLF) increased large-WSA andAS in surface layers, achieving macro- WSA contents like NV (~50%), while EG showed the lowest AS. At the heavier-textured Site 2, ICL and NT increased large-WSA (~50%) compared with CT (29.4%), which also had the highest micro-WSA and lowest AS, indicating structural degradation. In the sandy Site 3, RP and EG markedly enhanced large-WSAandAS, whereas CT again showed the weakest structural stability and highest micro-WSA. Across all sites, micro-WSA acted as the main sink for total and non-labile P—consistent with mineral–organic protection mechanisms in microaggregates (Six et al., 2000)—with microaggregates frequently accumulating >500–700 mg $kg^{-1}$ non-labile P under NT and CT.

Qmax generally decreased from large to micro aggregates and was highest in the clay-rich Site 2 (up to ~1330 mg $kg^{-1}$ under NV). In sandy soils, Qmax was lower (≈200–390 mg $kg^{-1}$) but remained greatest under RP. DNLP ratios showed that conservative systems (NV, RP, EG) retained more non-labile P in surface aggregates, whereas CT consistently displayed negative DNLP across aggregate classes, indicating vertical redistribution of legacy P linked to structural breakdown (Barrow, 2017).

Principal component analysis confirmed that IAS, NT and CT clustered with higher total P, non-labile P and Qmax, while NV, EG and RP were associated with higher AS and WSA but lower mineral P pools. Overall, IAS preserved or restored soil structure comparable to NV and, particularly in sandy Oxisols, enhanced the structural protection of P while supporting improved P-use efficiency and food security. These findings highlight soil aggregation as a key moderator of P legacy, buffering P transformations under contrasting land uses. Integrated systems provide a structural pathway to improve P-use efficiency and long-term sustainability in highly weathered soils.

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# Effectiveness of using the poultry-litter biochar pyrolyzed by different processes on soil available P

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**ABSTRACT**

Poultry litter is a useful fertilizer material. In Taiwan, it is estimated that the annual production of poultry litter about 2.5 million tons. To reduce environmental concerns from the raw litter materials disposal and direct application, converting raw litter to biochar is a promising recycling method. Biochar application in agricultural production is a potential resolution for plant nutrient supply and waste recycling. The effectiveness of biochar application to a soil on plant growth would be dominated by characteristics and application rates of biochar. In this study, two batches of soil incubation testing were conducted with different durations after application of poultry-litter biochar (PLC) for 30 and 90 days separately to access the effects of PLC application on soil available P. Pinchen series soil, which is an Oxisol in Taiwan, was used for illustration. The PLCs were derived with 6 different pyrolysis processes, which are the combinations of 3 pyrolysis temperatures (250℃, 350℃, and 550℃) and 2 annealing conditions (sealed and purged). The properties (i.e. pH value, EC, PZC, total P content, carbonate, and surface functional groups) of the PLCs were analyzed. Each PLC mixed with 100 g soil sample was added in each pot for incubation. The PLC application rates were 0%, 1%, 2%, 5%, 15 and 30%. The pots were placed in an incubator to keep the temperature at 25℃ and to maintain water content of soils in pots under field capacity about 0.7-fold soil saturated capacity. After incubation, the pH, EC and available P of incubated soil samples were analyzed. The results revealed that the pH, EC, total P and carbonate of PLC were increased with rising pyrolysis temperatures, but the CEC and functional groups of PLC decreased. The pH values of PLC were highly correlated with the carbonate; especially the pH of PLC exceeded 10 by 550℃ pyrolysis temperature. Compared with sealed annealing, purged annealing would enrich more CEC and surface functional groups of PLS. This reveals that the purged process shortened annealing to reduce the decomposition of functional groups on PLC surface. In addition, under the lower PLC applications (1% and 2% and 5%), the soil pH values significantly increased; even 15% and 30% PLC applications resulted in the pH being higher than 7. Also, the soil EC values were increased with PLC application rates and due to rising PLC pyrolysis temperatures. While the PLC application rates were higher than 15%, soil EC would exceed 2 dS $m^{-1}$. Furthermore, soil available P varied simultaneously with the changes of pH and EC, due to the PLC applications. Under the PLC application lower than 5%, soil available P would be increased with rising pyrolysis temperatures; however, while the application rates of PLC were approaching to more than 5%, soil available P continuingly increased with the additional applications of 15% and 30%.

**Keywords:** pyrolysis, annealing, poultry-litter biochar, phosphorous, agricultural byproducts

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# Rhizosphere AMF-Bacteria Synergy Driving Soil Phosphorus Activation in Maize//Soybean Intercropping

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## ABSTRACT

Maize and soybean intercropping plays an important role in enhancing crop yield, phosphorus (P) use efficiency and soil P activation in red soil. Soil microbial and mycorrhizal are critical for mediating soil P transformation under intercropping. However, the AMF-Bacteria interaction and the underlying mechanisms of intercropping driving soil P activation in red soil remains poorly understood. Based on a 7-year consecutive field experiment, two plantation models: maize monoculture and maize//soybean intercropping under four phosphate application rates (0, 60, 90, and 120 kg $P_2O_5 \cdot ha^{-1}$) on dryland red soil in Yunnan were compared, the effects of maize//soybean intercropping on maize yield, soil P fractions, the rhizosphere microbiome community, the arbuscular mycorrhizal fungal (AMF) and the phosphate solubilizing bacteria (PSB) were analyzed by integrating Illumina HiSeq sequencing and real-time quantitative PCR (qPCR). The underlying mechanisms of intercropping driving rhizosphere AMF-PSB synergistic interactions to promote soil P activation in red soil were discussed.

The results showed that, maize//soybean intercropping significantly increased maize yield, improved phosphorus use efficiency, increased the proportion and content of soil liable P pools, and enhanced soil P activation in red soil. Compared to maize monoculture, the grain yield of intercropped maize average increased by 45.97%, the yield sustainability index average increased by 58.87%, while the agronomic efficiency (AE) and apparent recovery efficiency (RE) of phosphorus fertilizers increased by an average of 48.53% and 28.68% across the 4 P levels. The proportion of the soil liable P pool average increased by 16.3%, in which the content of resin-extractable P (Resin-P) increased by 27.1%, the content of sodium bicarbonate-extractable inorganic P ($NaHCO_3$-Pi) increased by 16.9%, and the content of sodium bicarbonate-extractable organic P ($NaHCO_3$-Po) increased by 15.6%. Consequently, the soil phosphorus activation coefficient (PAC) average increased by 30.5%.

Maize//soybean intercropping reshaped the rhizosphere microbiome community. Intercropping significantly altered the rhizosphere AMF community structure, enhancing AMF diversity and enriching the *Glomus* genus with an relative abundance increase of 135.98%, enhancing the stability of the AMF co-occurrence network. Intercropping enhanced bacterial community diversity, significantly enriching phosphate-solubilizing bacteria (*Bacillus*) and antagonistic bacteria (*Streptomyces*), and strengthened the stability of cross-symbiotic networks between differential functional bacteria and AMF. This synergistic effect significantly upregulated key genes of soil P activation *phoD* and *pqqC*. Variance Partitioning Analysis (VPA) confirmed that the most important contributors to P activation was the synergistic effect of functional bacteria and AMF interaction, functional bacteria, and AMF, in order.

In conclusion, maize//soybean intercropping can synergistically promote soil P activation by reshaping the rhizosphere microbial community structure, enriching the abundances of both AMF and PSB, enhancing AMF-PSB cross-kingdom synergistic interactions, and upregulating the expression of key P activation genes, ultimately increasing maize yield and P use efficiency in red soil.

**Keywords:** Intercropping; Soil phosphorus activation; Arbuscular mycorrhizal fungi (AMF); Phosphorus-solubilizing bacteria (PSB); Red soil

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# Enhancing the functionality of agricultural soils in Mediterranean regions with biobased P fertilizers: nutrient cycling and soil microbial communities

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**ABSTRACT**

Phosphorus (P) phytoavailability in soils located in semi-arid regions, including Mediterranean areas, is commonly constrained by the presence of carbonates, which buffer soil pH around 8.0. Moreover, around 65% of these soils are degraded (low organic matter content, high soil erosion rates) resulting in a negative impact on soil functionality. Besides that, the increasing pressure on global phosphate rock reserves emphasizes the need for sustainable alternatives to mineral fertilizers to increase the resilience of agriculture. Recycled organic amendments may enhance soil functionality, particularly under the highly variable rainfall regimes typical of Mediterranean agroecosystems but their ability to supply P remains poorly understood. This study aimed to evaluate how different organic amendments improve the functionality of a Mediterranean agricultural soil, with emphasis on P cycling (as this is one of the most limiting nutrients under semi-arid conditions) and microbial communities (bacteria, archaea, and enzyme activities). A field experiment including a wheat–sunflower rotation in Andalusia (southern Spain) was conducted during two consecutive seasons to evaluate the immediate and residual effects of the organic amendments. A selection of composted organic amendments (including olive mill pomace, digestate, vermicompost, and urban solid residue), and stabilized amendments (based on plant residues) were compared with diammonium phosphate (DAP) and an unfertilized control. Additionally, pot experiments focused on evaluating how root traits and P uptake are modified after the application of organic amendments as a function of soil physicochemical properties were developed. Composted olive mill pomace and composted urban solid residue produced the largest increases in soil organic matter two years their application to the soil. Composted olive mill pomace triggered the strongest shifts in soil microbial community structure, followed by composted solid urban residue, whereas the latter most effectively enhanced nutrient cycling, improving the performance of mineral fertilizers (DAP) in terms of P use efficiency. Despite the drought-driven lack of significant yield differences, certain amendments increased aboveground biomass production and improved soil root exploration relative to CON. Enzyme activities related to C and P cycling were also stimulated by organic amendments, indicating improved biochemical soil functioning even under moisture-limited conditions. Overall, the results demonstrate that composted organic amendments can substantially modify soil functionality in Mediterranean agroecosystems, enhancing microbial processes, nutrient cycling and P-use efficiency despite severe drought, and support the transition toward more resilient cropping systems.

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# Evaluating the phosphorus release efficiency of duo-biochar to spring wheat

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## ABSTRACT

**Introduction**

High legacy soil phosphorus inputs from slurry and organic manures are an issue in intensively managed agricultural areas within Northern Ireland, Ireland and North America, reducing water quality. However, rapid fixation of manure supplied P to soil constituents causes between 70-90% of the applied phosphorus becoming unavailable to plants. Therefore, solutions are required to both retain excess phosphorus in the soils, thereby protecting freshwater and coastal habitats, and act as a slow-release fertiliser to provide plants with sufficient phosphorus during growth. Biochar, a carbonaceous material produced from the thermochemical conversion of biomass, can absorb phosphorus, and its capacity to do so is increased by modification with metals, such as iron (Fe). This experiment aimed to test the effects of Fe-doped biochar versus unmodified biochar on crop production, soil P availability and water quality.

**Method**

Fe-modified and pristine biochar were loaded with P and applied in a pot scale experiment at a rate equivalent to 10 t $ha^{-1}$ and compared to a biochar-free control. At 40-, 80- and 120- days following sowing, pots were leached with deionised water and the leachate measured for total (TP) and soluble reactive (SRP) phosphorus. Following leaching, crop and soil samples were taken and measured for available P.

**Results and Discussion**

Laboratory analysis is still ongoing, but preliminary results show a significant effect by modified biochar reducing TP leaching losses, however soil available P was unaffected between treatments. Modified biochar reduced the tiller number of the crop. This is potentially due to the slow release of P from the biochar during the establishment phase of the crop growth (~0-30 days), which is a crucial time for tillering. Whilst modified biochar did not increase soil P availability during the growing season, it did reduce P leaching losses, demonstrating its potential to mitigate excess P losses from agricultural soils.

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# Effects of organic fertilizer substitution on soil inorganic phosphorus (P) fractions and dynamics at the aggregate level: evidence from P fractionation and $^{33}P$ isotopic exchange kinetics

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## ABSTRACT

Effective phosphorus (P) management during organic fertilizer substitution requires more knowledge of how P pools are cycled within soil aggregates. The main objective of this study was to investigate the effects of two organic substitution types (i.e., animal- and plant-derived composts) of equal-N input on soil inorganic P fractions and dynamics at the soil aggregate scale in a two-year wheat-maize rotation system. To examine this objective, a combination of Hedley sequential P fractionation and $^{33}P$ isotopic exchange kinetics (IEK) was used. Results showed that the animal-derived fertilizer (i.e., pig manure, PM) presented the significantly highest soil available P ($NaHCO_3$-Pi, 31.6 ± 3.4mg $kg^{-1}$), due to 10-39 times higher P inputs compared with chemical fertilizer (CF) and plant-derived fertilizer (i.e., fruit tree pruning, FP) equivalents. In contrast, the FP treatment significantly improved $NaHCO_3$-Pi (25.1 ± 3.0 mg $kg^{-1}$) as compared to the CF treatment (16.6 ± 3.1 mg $kg^{-1}$) but with very little P input (16.8 *vs.* 65.7 kg $ha^{-1}$ $year^{-1}$). P cycling within soil aggregates can be better described by P dynamics derived from the $^{33}P$ IEK method rather than P pools derived from Hedley P fractions. Specifically, < 0.25 mm aggregates showed higher inorganic P transformation ability than > 0.25 mm aggregates as indicated by larger IEK parameters including water-extractable P, $r_{1min}/R$, m and extrapolated E-values. These results indicated that smaller fraction can largely bind free P, and this P is also highly exchangeable and can be transferred to the available P pool. Organic fertilizer shortened the time difference of P dynamics between aggregates (e.g., non-significances detected after 4 and 5 days in PM and FP but after 19 days in CF, respectively), indicating that organic substitution can buffer the robust P dynamics and reduce P mobility likely by soil aggregation because of the introduction of C-rich materials. In terms of crop production, both crop grain yields and P uptake were not significantly affected by different fertilization regimes. Plant-derived fertilizer could be a balanced organic substitute due to its low P input and surplus, and maintenance of P supply, whereas the animal-derived fertilizer may lead to imbalance, surpluses and environmental losses in well P-supplied soils.

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# Trait-mediated rhizosphere phosphorus strategies drive functional complementarity among coexisting desert shrubs

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## ABSTRACT

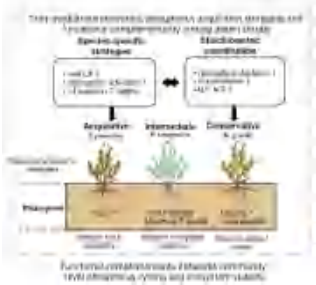
**Background and Aims** Phosphorus (P) limitation is a pervasive constraint in desert ecosystems, fundamentally shaping plant nutrient strategies, community structure, and biogeochemical cycling. However, the trait-based mechanisms that enable plant coexistence and ecosystem stability under chronic P scarcity remain poorly understood.

**Methods** In this study, we investigated rhizosphere and bulk soil P fractions, organ-level C: N: P stoichiometry, and $\delta^{13}C$ signatures in three co-dominant desert shrubs—*Kalidium gracile*, *Reaumuria soongarica*, and *Salsola passerina*, —to identify divergent P acquisition strategies and assess their ecological implications.

**Results** Our results revealed distinct functional strategies among species. *S. passerina*, a *$C_4$ chenopod*, employed a P-acquisitive strategy, characterized by rhizospheric enrichment of labile P (resin-P). *K. gracile* adopted a conservative strategy, marked by limited P mobilization, high leaf C: P ratios, and reliance on organic P mineralization and increased phosphatase activity. *R. soongarica* exhibited an intermediate buffering strategy, uptake moderate labile P with stem P storage, likely facilitated by root–microbial interactions. These species-specific strategies corresponded to differential root–soil–trait linkages and spatial variation in P availability. Despite divergence in rhizospheric processes, organ-level stoichiometric traits remained relatively conserved, indicating phylogenetic or biomechanical constraints on internal nutrient allocation. The coexistence of acquisitive, conservative, and intermediate strategies reflects functional complementarity in phosphorus use, which enables rhizospheric niche differentiation, minimizes interspecific competition, and supports community-level phosphorus cycling.

**Conclusion** Trait-mediated rhizosphere P strategies support plant coexistence and community stability in P-limited deserts, offering insights for biodiversity conservation and ecosystem management under resource stress.

**Keywords** Phosphorus acquisition strategies; Rhizosphere niche partitioning; Stoichiometry; Desert shrub coexistence; Functional complementarity



**Conceptual model** illustrating divergent rhizospheric P acquisition strategies among coexisting desert shrub species and their ecological consequences. The diagram integrates root–soil–plant interactions and organ-level stoichiometry to depict three distinct strategies: P-acquisitive (*Salsola passerina*), P-conservative (*Kalidium gracile*), and intermediate (*Reaumuria soongarica*). Each species mediates different rhizosphere P fractions, leading to functional differentiation in carbon–phosphorus trade-offs, tissue stoichiometry, and spatial niche partitioning. This functional complementarity supports more efficient phosphorus use and promotes community stability under extreme aridity.

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# Phosphorus in agricultural soils: status and dynamics

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**ABSTRACT**

To nourish humanity, vast quantities of phosphorus (P) have been applied to agroecosystems. Yet phosphate rock, a finite resource, dwindles rapidly. This P dilemma urgently requires sustainable solutions. To address this critical challenge, we conducted two major investigations: a global meta-analysis exploring the fate of P added to terrestrial ecosystems, and a systematic nationwide sampling of agricultural soils across China in 2024. Our global meta-analysis revealed alarmingly low plant P use efficiency, averaging a mere 12.6% in fertilization experiments. Concurrently, 4.4% of applied P fertilizer was lost from ecosystems. Over two-thirds of the added P accumulated in soils, predominantly locked in non-labile inorganic forms. Our extensive soil sampling across China uncovered striking spatial variations in P status and significant regional shifts, pinpointing alarming hotspots of both P-depletion and P-loss. Collectively, these findings underscore the critical necessity to improve our predictive understanding of soil P dynamics, and develop and implement sustainable P management approaches within agroecosystems.

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# Optimizing global cropland management to advance phosphorus sustainability

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**ABSTRACT**

Cropland phosphorus (P) is essential for global food security, yet its management faces significant challenges due to low phosphorus use efficiency (PUE), leading to resource depletion and nutrient loss from agricultural fields. The effectiveness of PUE-enhancing practices varies with local conditions, and the lack of a predictive framework has impeded the assessment of their global potential and their role in meeting food demand while staying within planetary boundaries. Here, we develop a machine-learning model to map global PUE geospatial variations for maize, rice, and wheat at 5 arc-minute resolution and quantify potential gains under optimized management. The model integrates key management, soil, and climate drivers to identify where P recovery is most constrained and where improvements are most attainable. Our results reveal global average PUEs of 23.9% for maize, 25.3% for rice, and 23.6% for wheat, with pronounced spatial heterogeneity across agroecological zones. Targeted management interventions could achieve absolute PUE gains of 9.5-10.2%, with exceptional potential in regions facing acute P deficits, particularly in Africa, where improved P recovery can simultaneously alleviate nutrient limitations and increase the effectiveness of scarce inputs. We further translate these spatially explicit PUE gains into implications for future P requirements and the global P budget under mid-century food-demand trajectories. Implementing these strategies could reduce global P demand by approximately 29% (6.3-7.7 Tg P $yr^{-1}$) by 2050, while constraining the planetary P surplus to 8.7 Tg P $yr^{-1}$, thus maintaining global P usage within planetary boundaries. Our spatially explicit framework illustrates how strategic agricultural management tailored to local constraints and opportunities can balance food security with planetary boundary compliance. It also provides a quantitative basis for prioritizing interventions that deliver the largest sustainability benefits.

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# Impact of Combined Manure and Mineral Fertilizer on Phosphorus Dynamics in Paddy and Drained Paddy Systems: Transitioning to Soybean Cultivation

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**ABSTRACT**

Phosphorus (P) limitation constrains agricultural productivity, particularly in drained paddy soils converted for soybean cultivation in South Korea. This five-year field study evaluated P dynamics at three soil depths (0–20, 20–40, and 40–60 cm) under three fertilization treatments: control, mineral fertilizer (NPK), and combined NPK plus manure compost (NPK + compost) in both paddy and drained paddy soils. Detailed P fractionation revealed distinct changes by treatment and depth. The NPK + compost treatment significantly enhanced available P, reaching 90.68 mg/kg in drained paddy soils and 68.24 mg/kg in paddy soils at 0–20 cm depth. Fe-bound P was the dominant inorganic fraction, peaking at 268.4 mg/kg with compost application in surface layers, accompanied by increases in Ca-bound and Al-bound P. Organic P similarly increased with compost addition, notably to 279.8 mg/kg at 20 cm in drained soils. Oxalate-extractable P ($P_{ox}$) and associated amorphous Fe and Al oxides ($Fe_{ox}$, $Al_{ox}$)—key in P binding—more than doubled under compost treatment. These increases declined with depth but remained significantly higher than control, indicating vertical stratification of P stabilization. The degree of phosphorus saturation ($DPS_{ox}$) rose to 20.3% in compost-treated surface soils, reflecting improved P retention but potential mobilization risks. Multivariate analysis confirmed fertilization and depth as primary drivers of P speciation, with organic amendments promoting stable organo-mineral complexes and enhancing P bioavailability. These findings highlight the critical role of integrated nutrient management in sustaining fertility and guiding phosphorus management in paddy-soybean cropping systems.

**Acknowledgments**

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# Characteristics of soil phosphorus profile distribution in degraded black soil areas and effects of tillage patterns on root zone phosphorus supply barriers

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**ABSTRACT**

As an important food production base in China, the long-term degradation of black soil in Northeast China has led to a decrease in soil phosphorus effectiveness, which seriously restricts crop productivity. In this study, different degraded black soil areas (wind-sand black soil area, thin black soil area, infertile black soil area and dry thin black soil area) in Songnen Plain and Liaohe Plain were taken as the objects of the study, and Hedley phosphorus grading method was adopted, and correlation and principal component analysis were applied to reveal the effects of soil phosphorus profile distribution characteristics of degraded black soil areas and cropping patterns on soil phosphorus effectiveness in the root zone through regional survey and long-term positioning tillage experiment (plowing and clearing, rotary ploughing and return to the field, tilling and returning to the field, deep loosening and returning to the field, and no-tillage and returning to the field) in the dry thin black soil area. The correlation and principal component analysis were used to reveal the distribution characteristics of soil phosphorus profile in degraded black soil area and the influence of tillage pattern on soil phosphorus effectiveness in the root zone. The main research results are as follows:

(1) There are significant differences in the phosphorus profile characteristics of different degraded black soil areas. The wind-sand black soil area is affected by high pH (9.06-10.05) and high calcium carbonate content (3.88%-5.08%), the active phosphorus percentage of each soil layer is extremely low (<10%), and the medium-stable and stable phosphorus dominates (>85%), which shows typical calcium and phosphorus fixation characteristics; the thin black soil area is affected by the neutral to weakly alkaline environment (pH 5.96-8.25) and high organic carbon content (14.08 g/kg), which is the main cause of the degradation of the soil. 14.08 g/kg), but the accumulation of calcium carbonate in the deep layer exacerbated phosphorus fixation; the soil in the barren black soil area was acidic (pH 4.72-6.32), with a prominent proportion of Residual-P, and phosphorus effectiveness was mainly regulated by nitrate nitrogen; the soil in the dry and thin black soil area was neutral to weakly alkaline (pH 6.28-7.48), and the surface layer (pH 6.28-7.48) showed typical calcium and phosphorus fixation characteristics; the soil in the thin black soil area was neutral to weakly alkaline, and the surface layer (pH 6.28-7.48) showed typical calcium and phosphorus fixation characteristics. 7.48), the surface layer (0-10 cm) of the soil promotes the release of reactive phosphorus due to the mineralization of organic matter, while the deep layer (60-80 cm) of the soil HCl-Pi accounted for a sharp increase (208.34 g/kg), and the distribution of phosphorus showed the synergistic regulation characteristics of calcium fixation and organic matter input.

(2) Tillage pattern significantly affected the effectiveness of soil phosphorus in the root zone. Due to the low carbon and nitrogen inputs and high pH, the active phosphorus in each soil layer was the lowest, and the proportion of stabilized and stabilized phosphorus in the deep layer was more than 80%. Compared with the tilled stubble, no-tillage, deep-pine and rotary tillage significantly increased the active phosphorus in the 0-20 cm layer, and the active inorganic phosphorus in the no-tillage treatment showed obvious epimerization; deep-pine and rotary tillage improved the aeration of the middle layer and synergized with quick-acting nitrogen to activate the active phosphorus in the 20-40 cm layer (the proportion of Resin-P increased by 14.29%);and tilled stubble only enhanced the active organic phosphorus in the 10-20 cm layer (the proportion of NaOH-P increased by 14.29%). Tillage can only enhance the active organic phosphorus (NaOH-Po) in the 10-20 cm soil layer, and the overall phosphorus activation effect is weak.

In conclusion, the distribution of phosphorus components in the degraded black soil area of Northeast China was dominated by soil degradation types, and no-tillage, rotary tillage, and deep-pine tillage significantly enhanced the phosphorus effectiveness by enhancing the carbon and nitrogen of the surface soil and optimizing the microenvironment of the soil in the root zone, which provided a key basis for conservation tillage in the black soil, and was of great significance for guaranteeing the food security and ecological sustainability of the region.

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# Does particle size of digestate-derived biochar affect phosphorus losses and fertilizer value? Evidence from a lysimeter study in a temperate soil.

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**ABSTRACT**

Phosphorus (P) is essential for plant growth and ecosystem productivity, yet its mismanagement in agriculture contributes to eutrophication and regional nutrient imbalances. Surpluses of manure-derived P in livestock-dense areas and deficits in arable regions underscore the need for strategies that efficiently recover and redistribute excess P. Biochar particle size has been shown to affect its short-term P fertilizer value, with smaller particles providing a higher initial P fertilizer value under controlled conditions. However, the long-term effect of biochar particle size on its P fertilizer value remains unknown. Furthermore, small particles may be susceptible to leaching, creating a potential trade-off between short-term fertilizer value and P leaching. Yet studies under temperate field conditions are scarce, highlighting the need to assess agronomic benefits and environmental risks of biochar application.

We conducted a two-year lysimeter experiment using twelve cylindrical polyester lysimeters (1.5 m depth, 1 m diameter) arranged in a randomized complete block design. They contained a sandy loam soil representing a dominant soil type in P-deficient regions of Denmark. Digestate biochar produced at 600°C was applied at 90 kg P $ha^{-1}$ either as powder (<125 µm) or pellets (>4 mm) at 3-5 cm depth. References treatments included mineral P fertilizer (90 kg P $ha^{-1}$ as TSP) and an unamended control. Maize biomass yield and P uptake were determined at harvest, and cumulative P losses in leachate were measured. After harvest in both years, soil samples from 0-10, 10-25, 25-50, and 50-100 cm depths were analyzed for soil pH, water- extractable P (WEP), and Olsen- P.

Biochar pellets reduced cumulative dissolved reactive P and total P losses compared to biochar powder in the first year after biochar application, while preliminary second year results showed similarly low P leaching across all treatments. In the first year, contents of WEP and Olsen-P in the 0-10 cm soil layer increased after application of powdered biochar and mineral P, compared to the control, whereas mineral P fertilizer resulted in higher contents of soil labile P in the second year. No treatment affected P-pools below 10 cm depth. A comparison of rhizosphere and bulk soil within each treatment during early growth showed significantly higher WEP in the rhizosphere under biochar pellets, with no differences in other treatments. Soil pH, maize biomass yield, and P uptake remained similar across treatments throughout the study.

Our findings suggest that pelletized digestate-derived biochar can mitigate P leaching compared to powdered biochar in the first year after application. Powdered biochar increased labile P in the upper soil layer during the first year, but neither biochar type posed a leaching risk in the second year. Therefore, pelletized biochar does not appear to constitute an environmental risk in terms of P loss down the soil profile in a sandy loam under temperate conditions.

# Cultivar-Dependent Cluster Root Strategies Underpin Phosphorus Use Efficiency in Macadamia Grown Under Low Phosphorus Conditions

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## ABSTRACT

Phosphorus (P) limitation is a major constraint in highly weathered subtropical soils, necessitating crop- and cultivar-dependent strategies for sustainable P use. Macadamia (*Macadamia* spp.), a Proteaceae tree crop adapted to P-impoverished soils, exhibits high P-use efficiency through formation of specialized cluster roots (1) and is widely cultivated in southern China, where Yunnan Province is the world's largest macadamia-growing area (2). However, cultivar-level variation in cluster-root development and P-use strategies remains poorly understood. We evaluated four widely-cultivated macadamia cultivars (HAES741, HAES788, Own Choice (O.C.), and hybrid H2) under normal-P (NP) and low-P (LP) supplies in hydroponic and soil-based pot experiments. Plant nutrient status, cluster-root traits, and rhizosphere processes were analyzed. Under LP, dry matter partitioning among roots, stems, and leaves was similar among cultivars, with no root–shoot trade-offs. However, P-use efficiency differed significantly. Leaf P concentration was significantly higher in HAES741, O.C., and H2 than in HAES788, with HAES741 and O.C. having the highest values, indicating preferential P allocation to photosynthetic tissues. Cultivars O.C. and H2 produced a greater number of cluster roots (~30 clusters plant$^{-1}$), than HAES741 (~10 clusters plant$^{-1}$) under identical LP conditions. Despite lower cluster root abundance, HAES741 exhibited high cluster-root acid-phosphatase exudation activity, reflecting a low-cost, high-efficiency strategy. It also had a shorter young phase of cluster-root development, but prolonged senescence, a stage associated with enhanced organic acid secretion. Oxalate, citrate, and malate were most abundant in exudates from HAES741 and O.C. The LP supply also stimulated cultivar-dependent differences in rhizosphere microbial community structure without changing the dominant phyla. Overall, macadamia P-use efficiency is governed by coordinated regulation of cluster-root number, developmental timing, and functional specialization, providing a mechanistic basis for reducing P fertilizer inputs and improving the sustainability of macadamia production in P-limited agroecosystems.

**Acknowledgments**

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# Organic P Mineralization in Agricultural Soils: Process Dynamics and Microbial Drivers

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**ABSTRACT**

Globally, soil organic P (Po) accounts for 30–65% of the total P in agricultural soils and thus acts as a significantly potential available P source. However, Po must be mineralized before becoming plant available. Currently, the relative contribution of Po mineralization to soil total P supply and the associated mechanisms controlling the mineralization process remain highly uncertain. Soil P (e.g., Po and inorganic P) status as well as biotic and abiotic properties may affect Pi transformation and Po mineralization. The objective of this study was to understand the relationships between soil Po mineralization rates and soil P pools and microbial-relevant metrics. For this, three farmland soils with comparable P status were collected from north China (Songyuan, Beijing and Dingxi). By using isotopic ($^{33}$P) dilution technique, the biotic and abiotic P fluxes was quantitatively assessed. Further, the communities of core functional genes driving Po mineralization (i.e., *phoC*, *phoD*) and their regulatory mechanisms were investigated. Results showed that the variation in the Po mineralization rate presented a dissociation from the variation in total Po content. This finding indicated the significance of decomposing ability of soil microbes in addition to substrate quantity, which was verified by the difference in alkaline phosphatase activity. Regarding the community of phoD-harboring microorganisms across the three soils, core taxa such as *Aureimonas, Pleomorphomonas, Psychrobacter, Thalassospira, Bradyrhizobium, Aquabacterium* may play significant roles in promoting enzymatic activity and in turn Po mineralization. This work provides a theoretical foundation for enhancing P use efficiency and promoting sustainable agricultural development.

# Incorporating Chinese milk vetch and rice straw promoted inorganic phosphorus mobilization through assembling phosphate-solubilizing bacteria in rhizosphere

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**ABSTRACT**

Previous study showed that incorporating Chinese milk vetch (CMV) and rice straw combined with 50% of recommended P fertilizer (MSP50) increased rice straw and grain yields compared with the conventional P fertilizer application treatment (P100). However, the responses of rhizobacterial community and inorganic P mobilization strategies to the incorporation practice with partial mineral P fertilizers remain unclear. Hence, a pot study based on the field trial was conducted to investigate the effects of CMV and rice straw incorporation on low-molecular-weight organic acids (LMWOA) concentrations, soil P fractions, and the rhizobacterial community. Results showed there were no significant differences in both shoot and root P accumulations between P100 and MSP50 treatments. At rice booting stage, MSP100 treatment significantly increased $Ca_2$-P and Fe-P by 14.8% and 28.7%, respectively, while reducing Al-P and O-P by 14.4% and 6.2%, respectively, compared with P100 treatment. The $Ca_2$-P fraction was positively correlated with oxalic and malic acids contents in rhizosphere. In MSP0 and MSP50 treatments, where P was deficient or highly utilized, phosphate-solubilizing bacteria (PSB) were recruited to improve P mobilization through LMWOA secretion. Based on the correlation between bacterial genera and P fractions, *Bacillus*, *Flavisolibacter*, *Massilia*, *Intrasporangium*, and *Gemmatimonas* were identified as PSB in the present study. The MSP100 treatment resulted in a significantly higher Shannon index but a lower Simpson index than other treatments, indicating the higher bacterial community diversity but lower abundance of the dominant species, which was also supported by the significantly higher MBP content. Consequently, incorporation of CMV and rice straw combined with half of the recommended mineral P fertilizer reduced the diversity of soil bacteria but increased the abundance of PSB, thus reducing the energy consumption of bacteria and enhancing soil inorganic P mobilization.

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# Multi-benefits of wastewater phosphorus recovery for croplands in China

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**ABSTRACT**

Phosphorus (P) is essential for global food production, yet it faces a dual crisis of increasing resource scarcity and escalating environmental pollution driven by wastewater P discharge. Recovering P from wastewater systems therefore represents a critical strategy to simultaneously address resource security and environmental sustainability. However, systematic assessments of this potential remain limited, particularly with respect to recovery pathways, regional heterogeneity, and integrated environmental and economic benefits. This gap is especially pronounced in China, where both P scarcity and wastewater P pollution are severe. Using high resolution data from more than 600 cities, this study quantified P waste flows and evaluated their recovery potential across China. We estimate that the national P recovery rate reached 21.9% in 2022, with pronounced spatial disparities. Under best available technology scenarios, P recovery from wastewater could be tripled to 189,600 tonnes, offsetting up to 6.6% of annual cropland P fertilizer demand. This recovery would simultaneously reduce waterborne P pollution by 30% and generate economic benefits of approximately 356 million USD. Our results provide a robust quantitative foundation showing that wastewater P recovery is a cost-effective alternative for achieving a synergistic triple win across food security, environmental protection, and economic gains.

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# Land use controls soil phosphorus pools but not sorption mechanisms: insights from piecewise structural equation modelling

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## ABSTRACT

Phosphorus (P) sorption in soils is a key process regulating both plant P availability and the risk of soil P saturation and transfer to aquatic ecosystems. While the physicochemical controls of P sorption are well established, the extent to which land use modifies sorption mechanisms versus soil P pools remains insufficiently quantified within an integrated framework.

In this study, we analysed 80 soil samples equally distributed among four land-use types (forest, grassland, cropland, and kitchen gardens) to disentangle the direct and indirect effects of land use and soil properties on P sorption, availability, and saturation. Phosphorus sorption parameters were derived from isotherm experiments, including Langmuir maximum sorption capacity (Qmax) and sorption affinity (b). These parameters were related to soil P pools, oxalate-extractable Fe and Al, pH, soil organic carbon (SOC), texture and cationic exchange capacity (CEC) using a piecewise structural equation modelling (SEM) approach in R.

Land use exerted a strong control on soil P pools and SOC, explaining 32%, 41%, and 66% of the variance in total P, oxalate-extractable P, and SOC, respectively. In contrast, sorption mechanisms were largely independent of land use. Sorption capacity (Qmax) was primarily controlled by Fe and Al oxides and SOC, whereas sorption affinity (b) was strongly enhanced by Fe oxides but significantly reduced by SOC, highlighting contrasting organo-mineral effects on P retention. Both sorption parameters exerted a negative control on plant-available P, with sorption affinity emerging as the dominant driver. Soil P saturation (DSP) was mainly governed by oxalate-extractable P, counterbalanced by the pool of reactive Fe and Al oxides, with a secondary influence of soil pH.

Overall, this integrative analysis demonstrates that land use primarily influences soil P dynamics through long-term accumulation of P and organic carbon rather than through changes in fundamental sorption mechanisms. By disentangling direct and indirect controls, the piecewise SEM framework provides new insights into the hierarchy of processes governing soil P availability and saturation, and helps clarify trade-offs between soil fertility management and environmental risk.

# Long-term biochar application influences phosphorus and associated iron and sulfur transformations in the rhizosphere

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**ABSTRACT**

The effects of long-term biochar application on soil phosphorus (P) flux across the root-soil interface and its availability in the rhizosphere of rice (*Oryza sativa* L) remain unclear. We used diffusive gradients in thin films (DGT), laser ablation-inductively coupled plasma mass spectrometry, and planar optode sensor techniques to characterize, *in-situ*, the 2D heterogeneity and dynamics of rhizosphere soil P, iron (Fe), sulfur (S) and trace element fluxes, dissolved oxygen and pH in paddy soil, after 10 years of biochar application. Compared to the control (no biochar applied), biochar applied at 4.5, 22.5 and 45.0 Mg $ha^{-1}$ $yr^{-1}$ decreased rhizospheric P fluxes by 11.6%, 63.4% and 79.0%, respectively. This decrease under biochar treatments was attributed to changed redox status of Fe and S caused by the lower dissolved oxygen in rhizosphere soil and increased soil pH induced precipitating of soluble inorganic P into insoluble P forms, such as calcium-bound and residual P that are unavailable for crop uptake. Higher application rate of biochar resulted in lower As and Pb fluxes in rice rhizosphere and their availabilities for crop uptake. The *in-situ* observation results in rice rhizosphere at μm-scale after 10 years of biochar addition directly showed the complex effects of long-term biochar and rhizosphere heterogeneity on P transformation process.

# Molecular-level understanding of transformation mechanisms of P in the calcareous agricultural soils

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**ABSTRACT**

With the increasing pressure on phosphorus (P) resources and global water eutrophication, the development of sustainable land management is pushed forward by detailed knowledge on the nature and fate of phosphorus (P) in agricultural soils. Therefore, understanding the transformation of P in the agricultural soils is of vital importance for effective management of P nutrient. Calcareous soils, in the Northern area of China, are important agricultural lands for crop production, but accumulated large amount of P as legacy P in the soils. Multiple reasons, including P fertilization regime, tillage practices, crop straw returning etc., could contribute the accumulation of legacy P in soils. However, the transformation mechanism of P in the agricultural calcareous soils remains largely unknown. Here, we showed the different impacts of long-term P fertilization regime and tillage practices on the transformation of P in calcareous soils using solution 31P nuclear magnetic resonance; P K-edge X-ray absorption near-edge, XANES and micro X-ray fluorescence and XANES spectroscopic techniques. We found long-term P fertilization regimes and tillage practices significant affected the availability and speciation of P in the calcareous soils. These results facilitate more effective management of P in agricultural calcareous soils

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# Earthworms enhance soil phosphorus cycling but plant responses differ among earthworm ecological categories

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**ABSTRACT**

Earthworms are integral to soil processes and influence plant growth and phosphorus (P) nutrition. We investigated the role of earthworms in the P cycle by synthesizing data from 181 studies, of which 22 % were field observations and 78 % were from pot or mesocosm experiments. Earthworms increase the concentration of soil Olsen P and microbial P, phosphatase activity, and plant biomass. Deep-dwelling epi-anecic and anecic earthworms are more effective than other ecological groups at increasing the soil available P, although surface-dwelling earthworms (epigeic and endogeic) contribute more effectively to plant P uptake. The increase of plant biomass by earthworms decreases with increasing organic matter content, but Olsen P concentration and plant P uptake show the opposite trend. Moreover, the impact of endogeic earthworms on P is sensitive to soil organic matter content. The positive effects of earthworms on P cycling are more pronounced under acidic and alkaline conditions than under neutral conditions (6.5–7.5). Finally, the increased available P concentration due to earthworms directly stimulates microbial P uptake, while all three main ecological categories of earthworms indirectly stimulate root growth and increase plant P uptake. Overall, earthworms can effectively promote P cycling in ecosystems, with a more significant effect in nutrient-poor soils.

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# An innovative approach for measuring soil microbial biomass P

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## ABSTRACT

Determining microbial biomass phosphorus (MBP) in soils is essential for understanding soil P cycling in agricultural systems where fertility management is progressively shifting from mineral fertilization toward more integrated and sustainable strategies. The latter approaches rely on recycled fertilizers, enhanced crop diversity, and preservation of soil biological functioning. Microbial biomass can represent a substantial and dynamic pool of readily available P even to plants following microbial turnover, making its accurate quantification critical for P management in the soil-plant sysyem. The classical fumigation–extraction (F–E) method is widely used to estimate MBP; however, it relies on chloroform fumigation, which poses health and environmental risks. In addition, several methodological limitations have been highlighted. In particular, P released after microbial cell lysis may be rapidly adsorbed onto organo-mineral colloid surfaces or precipitated in soils by polyvalent cations, leading to an underestimation of MBP. Although the application of P spikes after fumigation is commonly used to correct for these effects, this approach may still be inaccurate, as it does not account for soil–P interactions occurring during the fumigation period.

To address these limitations, three alternative approaches to the classical fumigation–extraction (F–E) procedure were evaluated using three soils differing in key physical and chemical properties that influence P dynamics (i.e., clay, carbonate, and Fe-oxide contents). Two approaches involved liquid fumigation combined with the use of P sinks, specifically an anion exchange resin and a filter paper impregnated with iron oxides, the latter being tested for the first time for this purpose. The third approach employed the recently proposed microbial lysis induced by high-pressure $CO_2$ fumigation, eliminating the need for chloroform and reducing procedural risks.

Results showed that MBP varied significantly among soils confirming the strong influence of soil properties on P adsorption and precipitation processes. The inclusion of P sinks consistently resulted in higher MBP estimates, highlighting a key limitation of the classical F–E procedure, which generally underestimates MBP. Among all tested approaches, the use of chloroform fumigation coupled with iron oxide–impregnated paper strips proved to be the most effective, yielding on average a 52% increase in MBP compared with the classical F–E approach, while also exhibiting the lowest variability and highest reproducibility.

This low-cost, safe, and innovative approach, after validation with $^{31}P$, could represent a significant advancement for accurately quantifying MBP and could substantially improve our understanding of P dynamics in agroecosystems, supporting the transition toward more diversified and sustainable soil management practices.

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# Sulphur Impregnated Biochar Synchronizes Phosphorus Release from Occluded Pools while Enhancing Carbon Stabilization

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## ABSTRACT

Modern agricultural systems face a pervasive phosphorus (P) paradox, wherein P availability is often limited despite adequate fertilization. Sulphur (S), a naturally occurring element, possesses the inherent capacity to mobilize P from recalcitrant soil pools, thereby offering a promising strategy to alleviate P limitation. To leverage this phenomenon, S-enriched biochar (SEB) was prepared to synchronize P mobilization with carbon (C) stabilization, providing a novel approach to enhance P availability and promote soil fertility. A controlled incubation experiment was conducted to assess SEB's efficacy in modulating P dynamics and C stabilization in soil. The experimental design included four biochar treatments [pristine biochar (PB), two SEB types (SEB1 and SEB2, with low and high S contents, respectively), and an unamended control (CK)]. These treatments were evaluated under two P fertilizer rates [75% (P75) and 100% (P100) of the recommended dose] over 120 days. The results demonstrated that SEB significantly enhanced P availability and cycling, as evidenced by increases in labile, moderately labile, and non-labile P fractions. Notably, SEB application resulted in substantial increases in resin-P (84.4% at P100 and 67.2% at P75) and $NaHCO_3$-Pi (31.6%-34.5%) concentrations, accompanied by a marked rise in $NaHCO_3$-Po, indicating enhanced microbial P cycling. Moderately labile P pools, such as NaOH-Pi, peaked at day 60, with increases of up to 9.9% (P100) and 20.8% (P75), and were accompanied by continuous increases in NaOH-Po and Dil. HCl Pi. Furthermore, SEB also elevated the non-labile P fraction (residual P), indicating improved P stabilization. Additionally, SEB stimulated C-, P-, and S-acquisition enzyme activities, suggesting enhanced microbial nutrient cycling. In summary, these findings demonstrate that SEB provides a low-input, multifunctional strategy to improve P cycling, enhance SOC, and strengthen C-stabilization in agroecosystems, with significant potential for sustainable agricultural practices.

**Keywords:** Carbon stability, Enzymatic activities, Phosphorus fractions, Soil health, Sulphur enriched biochar.

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# Phosphorus Maximum Sorption Capacity in Soils from Paraná State in Southern Brazil

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**ABSTRACT**

Soils located in the state of Paraná, in southern Brazil, are largely weathered and characterized by the presence of iron and aluminum oxides and hydroxides, which confer a high capacity for phosphorus (P) sorption. The maximum P sorption capacity (MPSC) corresponds to the maximum amount of P that a soil can retain and can be used as a complementary parameter to understand P dynamics in soils. The objective of this study was to estimate the MPSC of 26 representative soils from the state of Paraná and to evaluate its relationship with physicochemical and geographic attributes, especially clay content, total organic carbon (TOC), remaining P, and altitude. The MPSC was determined by fitting the Langmuir isotherm. TOC was estimated by wet combustion using a dichromate solution followed by titration with ammonium ferrous sulfate. Remaining P was determined from the P concentration in solution after equilibrating the soil with a standard solution containing 60 mg $L^{-1}$ of P. Clay content was determined by the hydrometer method after mechanical dispersion and stabilization of the samples, using 1 mol $L^{-1}$ NaOH as the chemical dispersant. The sampled soils showed MPSC values ranging from 30 mg $kg^{-1}$ to 2930 mg $kg^{-1}$, with most presenting values above 500 mg $kg^{-1}$. A positive correlation was observed between MPSC and clay content ($\rho = 0.41$, $p = 0.041$), indicating a greater P retention capacity in soils with higher clay contents. Remaining P showed a negative correlation with MPSC ($\rho = -0.98$, $p = 2.8 \times 10^{-7}$), confirming its validity as an indirect and practical indicator of P retention capacity. TOC showed a positive correlation with MPSC ($\rho = 0.92$, $p = 1.5 \times 10^{-11}$), indicating that soils with higher organic matter content have a greater capacity to retain P. Altitude was also positively correlated with MPSC ($\rho = 0.73$, $p = 2.7 \times 10^{-11}$), demonstrating the indirect influence of pedogenetic factors, as well as greater or lesser preservation of organic matter under higher- altitude conditions. Overall, the results showed that clay content, as an indicator of P retention capacity, shows lower sensitivity to the mineralogy of the clay fraction when compared with remaining P. TOC and altitude do not directly control MPSC in the same way as the mineral fraction. Their relationship is modulated by pedogenetic processes and by climatic and textural soil conditions, which influence the preservation of soil organic matter and the mineralogy of the clay fraction. These results contribute to the understanding of P dynamics in weathered soils and to a more efficient management of soil and fertilization.

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# Keystone microbes mediate root traits and phosphorus uptake to enhance maize crop productivity in intercropping systems

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**ABSTRACT**

*Background and aims* Intercropping has been demonstrated to enhance crop productivity and phosphorus (P) uptake, in which root-microbe interactions played crucial roles. Our previous results showed that this beneficial effect of intercropping depends largely on a match between root traits and rhizosphere processes. However, little is known about the role of soil microbial communities in underground processes.

*Methods* Using a long-term field experiment with three P-fertilizer application rates and five cropping systems of maize, we integrated crop productivity, root physiological traits, root morphological traits and microbial amplicon sequencing data.

*Results* Our findings revealed that intercropping significantly enhanced maize crop productivity and P uptake, accompanied by increased plasticity of morphological and physiological root traits compared with monoculture. Additionally, intercropping with different companion crops significantly altered the soil microbial community structure of maize, while P-fertilizer application rates had minimal effect. Network analysis showed that intercropping promoted more complex and stable microbial networks characterized with increased cooperative relationships, relative to monoculture. The relative abundance of keystones enriched in intercropping systems were positively correlated with crop productivity and P uptake, explaining 41.11% of the variation in maize grain yield. Structural equation modeling (SEM) further indicated that keystones enhanced grain yields of maize by inducing carboxylate secretion and fostering more acquisitive root morphological traits.

*Conclusion* Our study elucidates how intercropping optimizes root-microbe synergies to improve P efficiency, highlighting the potential for targeted manipulation of keystone microbial taxa to enhance P acquisition and crop performance in sustainable agricultural systems.

# Seabirds Bearing Light

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**ABSTRACT**

Seabirds have a vital ecological role as linkage service between marine and terrestrial ecosystems. The amounts of excreted P inputs by seabirds to soils is ~100 Gg P yr and similar in magnitude to other fluxes in global P cycles (Otero et al. 20218). The studies on resulting 'ornithogenic soils', terrestrial environments significantly altered by the accumulation of large amounts of materials in bird colonies (e.g., guano, feathers, eggshells) mainly focus on the cold or wet regions of our planet. However, even in the driest place on earth, the hyper-arid core of the Atacama desert we find breeding seabirds. This unique situation allows here, due to the absence of co-founding vegetation P inputs, to precisely quantity such 'marine derived' seabird total and soluble P soil inputs to terrestrial ecosystems. Enlightenment on the actual baseline contribution and importance of seabirds (and birds in general) to soil P provision, is critical for future design into approaches to sustainable optimizing of nutrient management and ecosystem functionality, especially in the wider context of the worrying global decline in bird numbers and its diversity.

**Acknowledgments**

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# Integrating regional critical boundaries and nitrogen-phosphorus limitation for global water quality

## ABSTRACT

Intensive crop production in recent decades has greatly increased nitrogen (N) and phosphorus (P) delivery to surface waters, causing severe water quality degradation and widespread eutrophication. Although regional safe boundaries for N delivery to surface waters have been proposed to support sustainable food production, comparable boundaries for P remain absent. Spatial variations in molar N:P ratios in nutrient delivery from cropland reveal region-specific nutrient imbalances, underscoring the need for differentiated nutrient management across regions. Using a spatially explicit modeling framework, we show that aggregating regional boundaries yields global boundaries of 7.3 and 1.0 million tons per year for N and P delivery to surface waters, respectively. In 2020, actual delivery exceeded these limits by 53% for N and 375% for P. Despite the greater magnitude of P exceedance, prioritizing N management proves to be a more effective strategy for mitigating eutrophication in most world regions, given the widespread occurrence of N limitation in aquatic ecosystems (N:P < 16). Integrating boundary exceedance with nutrient limitation analysis indicates that targeted nutrient reduction efforts could reduce global N and P delivery by 73% and 61%, respectively, providing a feasible pathway to restore water quality and protect aquatic ecosystems.

# Exploring characterization methods and thresholds of carbon-phosphorus ratio for promoting crop growth and microbial phosphorus activation

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## ABSTRACT

To investigate the impact of microorganisms on enhancing crop phosphorus nutrition after increasing the soil carbon-to-phosphorus ratio by adding carbon sources in calcareous soils, and to clarify the key thresholds and optimal characterization methods of soil carbon-to-phosphorus ratio in farmland, this study designed a two-factor randomized block experiment. Carbon was added at levels of 0, 30, 60, 120, 180, 240, 360, and 480 mg/kg in single applications, with soil available phosphorus levels at 9 mg/kg, 22 mg/kg, and 50 mg/kg. By establishing relationships between indicators such as SOC/Olsen-P, DOC/Olsen-P, and DOC/Pw, and microbial phosphorus-solubilizing ability, crop biomass, and phosphorus uptake, the study analyzed the impact of carbon-to-phosphorus ratio regulation on microorganisms for efficient utilization of accumulated phosphorus. The following conclusions were drawn:

1. Under different levels of available phosphorus in soil, with the increase of carbon addition, the biomass, phosphorus uptake, and soil microbial biomass phosphorus of plants all increase, while the available phosphorus and alkaline phosphatase activity in soil show a trend of first increasing and then decreasing.

2. SOC/Olsen-P is the best indicator of the relationship between the carbon-phosphorus ratio in calcareous soil and crop biomass and phosphorus uptake. According to the linear plus plateau model, the regulation threshold of the carbon-phosphorus ratio in calcareous soil is 745~867.

In summary, this study found that regulating the soil carbon-phosphorus ratio can enhance microbial activity and promote crop growth and phosphorus absorption. It clarified the threshold value of carbon-phosphorus ratio and its characterization indicators for promoting crop phosphorus absorption, established a method for altering the soil carbon-phosphorus ratio to regulate indigenous microorganisms and promote phosphorus activation and turnover, and provided a theoretical References for efficient utilization of soil phosphorus.

**Keywords:** carbon-phosphorus ratio, microorganisms, phosphorus fertilizer utilization rate

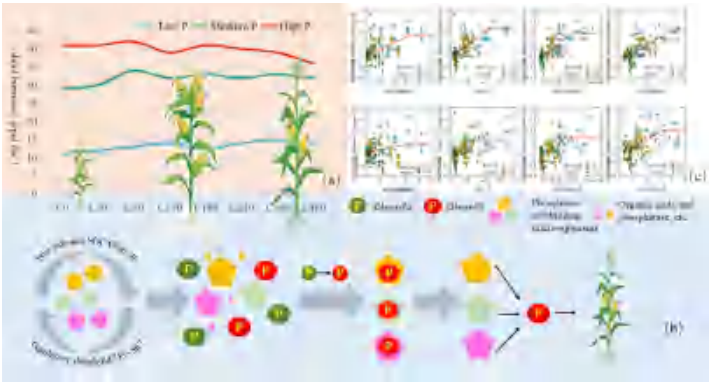


Figure 1. Under different soil phosphorus levels, the relationship between carbon source gradient and aboveground biomass of maize (a), the relationship between underground phosphorus-solubilizing microorganisms and crop phosphorus supply (b), as well as the correlation indicators between carbon-phosphorus ratio and biomass, phosphorus uptake (c).

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# Long-term green manuring increases phosphorus availability in soil by modifying microbial functional genes and enzyme activities

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**ABSTRACT**

Substitution of mineral fertilizers with milk vetch (*Astragalus sinicus* L.) organic fertilization strongly influences the dynamics and availability of phosphorus (P) in soil. How milk vetch organic fertilization affects the specific roles of P cycling functional genes in soil and, in turn, the mechanisms of altered P turnover remain unclear. Soil samples were taken from a 10-year field experiment that included mineral fertilizer and partial substitution of mineral fertilizer with milk vetch, together with an unfertilized control. The P-cycling functional genes in soil determined by metagenomics were related to phosphatase enzyme activities and P fractions with various availability. Milk vetch substitution decreased soil total P and $NaHCO_3$-OP (8 and 65%) but maintain similar available P and high phosphatase activities compared with mineral fertilizer, indicating a net solubilization/mineralization of soil P occurring in response to milk vetch substitution. The Proteobacteria, followed by Chloroflexi, Acidobacteria, Actinobacteria, Nitrospirae, Verrucomicrobia, and Gemmatimonadetes were the most abundant bacteria phyla involved in soil P-cycling. Shifts in P-cycling functional gene community were more related to soil total N and the ratio of SOC to total P. The relative abundance of P-cycling functional genes, increased the production of PQQ-GDH (*gcd*, *pqqE*), fumaric acid (*fumC*), acetic acid (*aldh*), acid phosphatase (*phoN*), alkaline phosphatase (*phoD*), the catabolism of organophosphonates (phnJ, phnN, and phnW) and the dissimilation of glycerol-3-phosphate (*glpB*, *glpF*, and *glpR*) by 4%–80%. Phosphatase activities increased with milk vetch substitution, because of raised abundance of related genes and gene-harboring communities (especially Chloroflexi). The *phoN* gene was the key predictor of organic P mineralization and thus available P. Overall, milk vetch substitution increased the P-acquiring enzyme activities and boosted the involvement of the functional genes in P cycling, which in turn stimulated P bioavailability. These results highlight the connections between milk vetch substitution and P cycling functional genes, which also have implications for offsetting the future demand for P mineral fertilizer by milk vetch substitution in agricultural systems.

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# Long-term Biochar Application Enhances Carbon-Phosphorus Co-stabilization and Mitigates Methane Emissions in Flooded Rice Systems

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**ABSTRACT**

Biochar is increasingly promoted as a climate-smart amendment, yet its long-term effects on nutrient retention and greenhouse gas emissions in flooded rice systems remain poorly resolved. Here we combine a 13-year field trial with graded straw biochar applications (0-22.5 t $ha^{-1}$ $season^{-1}$) and a 60-day anaerobic incubation of year-13 soils, to investigate how mineral and microbial processes regulate soil organic carbon (SOC), phosphorus (P), and methane ($CH_4$) dynamics. Long-term biochar progressively depleted Fe oxides and enriched Ca phases, promoting the formation of Ca bridged OC-mineral-P complexes that co-stabilize OC and P. Under prolonged anoxia, soils amended with high rates of biochar exhibited 2.5-3.2 fold slower Fe(III) reduction and delayed sulfate reduction, resulting in 53-80% lower $CH_4$ emissions and 60-71% P release relative to the no-biochar control. Nanoscale imaging and microbial profiling corroborated this mineral transition, showing a shift toward redox-resilient organo-mineral complexes and microbial communities associated with suppressed methanogenesis and enhanced nutrient retention. These findings provide the long-term field-based evidence that biochar can simultaneously sustain crop productivity, enhance C and P retention, and mitigate $CH_4$ emissions in flooded rice agroecosystems. Our findings highlight biochar's potential as a scalable nature-based strategy for integrating nutrient management with climate mitigation in global rice production.

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# Iron-based Adsorbents for Wastewater Treatment and Phosphorus Recovery

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**ABSTRACT**

The Philippines faces a phosphorus (P) paradox, characterized by persistently low yields among rural farmers due to P deficiency in soils, contrasted with P surpluses in urban and intensively farmed regions. Aiming for a more circular P use, this study evaluated three iron (Fe)-based adsorbents, i.e., synthetic layered double hydroxide (LDH), ferrihydrite, and schwertmannite, for P removal from synthetic solutions and real wastewater. Full isotherms for the three adsorbents were first established using synthetic P solutions. A subsequent comparative experiment evaluated adsorption at matched concentrations (5, 8 and 16 mg P $L^{-1}$) in both synthetic solutions and wastewater collected from sewage treatment plant, a dairy milking facility and a dairy processing plant. Langmuir isotherm indicated that synthetic LDH exhibited the highest adsorption capacity at 19.31 mg P $g^{-1}$, nearly double ferrihydrite (10.33 mg P $g^{-1}$), while schwertmannite was lowest (2.95 mg P $g^{-1}$). Freundlich models provided the best fit, suggesting multilayer adsorption. P uptake by adsorbents peaked in synthetic P solutions at 16 mg P $L^{-1}$ (~7 mg P $g^{-1}$ for LDH and ferrihydrite) but declined markedly in wastewater (~4-5 mg P $g^{-1}$ ). Synthetic LDH and ferrihydrite achieved near-complete P removal in synthetic solutions; however, their efficiencies declined by more than 90% in wastewater matrices. In contrast, schwertmannite exhibited superior performance under real wastewater conditions, attaining 60% removal at the lowest tested concentration. These findings highlight that removal efficiency was influenced by both sorbent properties and matrix chemistry. Overall, Fe-based adsorbents demonstrate strong potential for P recovery, offering a dual strategy to mitigate wastewater P excess and address soil P deficiencies in crop production systems.

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# Recycling lake sediment for use in agriculture: insights from laboratory and field experiments

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**ABSTRACT**

Recycling lake sediments as phosphorus (P) fertilisers offers a promising pathway to close nutrient cycles, reduce reliance on synthetic P inputs, and potentially mitigate P losses to freshwater systems. Within a broader context, lake sediments arise as a by-product of lake restoration initiatives across Europe, such as the FERRO project (Fostering European Lake Restoration). This project, alongside other restoration approaches, involves the removal of substantial quantities of nutrient-rich sediments as part oflake recovery strategies. These sediments have been extensively monitored and are known to contain high concentrations of P. Their reuse in agricultural systems as P fertilisers therefore represents an opportunity to valorise a restoration by-product, enhance nutrient recycling, and support both sustainable agriculture and long-term lake restoration outcomes. Here, we present results from studies evaluating the use of lake sediment as an alternative P fertiliser under both controlled (I) and field conditions (II). I) A 45-day pot experiment with pea (*Pisum sativum* L.) was conducted using lake sediment and mineral fertiliser as P sources, alongside an unfertilised control. Plant biomass, nutrient uptake, and rhizosphere soil properties, such as nutrient availability, cation exchange capacity (CEC), and enzyme activities, were assessed. (II) A 78-day field experiment with pea was established at an agricultural site near the lake where sediment dredging had occurred, comparing the same treatments. In the pot experiment, P source influenced both plant and soil responses with sediment-amended treatment producing biomass comparable to mineral fertiliser, while enhancing nutrient uptake, CEC, and rhizosphere functionality. In the field experiment, no statistical differences in biomass were detected among P sources, although both P treatments tended to produce higher biomass compared with the unfertilised control. Furthermore, sediment-amended plots in the field showed indications of improved below-ground responses and a reduced potential risk of P leaching compared with mineral fertiliser treatments, based on water-extractable P, which was higher in the mineral-fertilised treatment. Overall, these findings indicate that dredged lake sediment can function as an effective P source under controlled conditions and may deliver environmental benefits under field conditions. Recycling lake sediment as a fertiliser supports circular nutrient management and represents a promising strategy within European lake restoration initiatives; we speculate that these effects may be even more pronounced in agricultural systems with lower background soil P availability, as the soil used in our trials had a high P status.

**Keywords:** phosphorus-use efficiency, lake restoration, circular economy, biostimulants, sustainable agriculture.

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# Direct evidence for basaltic mineral weathering in cropland revealed by X-ray powder diffraction analysis

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## ABSTRACT

Enhanced rock weathering involves crushing rocks, such as basalt, and applying them to cropland to accelerate the natural weathering of basaltic minerals, including plagioclase (e.g., $CaAl_2Si_2O_8$) and pyroxene, thereby removing $CO_2$: $CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Ca^{2+} + 2HCO_3^-$. Despite numerous recent studies, direct evidence of basaltic mineral weathering in soils is lacking. Here, we applied quantitative X-ray powder diffraction (XRPD) to detect changes in basaltic minerals in cropland.

A field experiment was conducted in a buckwheat field with brown lowland soils (pH 6.0) in Fukushima, Japan, from July 27 to October 12, 2022. Two treatments were set: without basalt powder (control) and with basalt powder applied at 150 t $ha^{-1}$. Soil samples were collected from the surface before planting, and from both the rootzone and the non-rootzone after harvest. The mineral composition of air-dried, 2 mm-sieved soils was quantified by XRPD [1]. Soil water samples at 10 cm were collected on September 2 and 23 to determine pH and inorganic carbon, and bicarbonate ($HCO_3^-$) concentration was calculated.

Major basaltic minerals in the basalt were plagioclase (i.e., labradorite [31.1 wt.%] and bytownite [36.2 wt.%]) and pyroxene (10.8 wt.%). Basalt application significantly ($p < 0.05$) increased these minerals in soils. After cultivation, bytownite and pyroxene in the buckwheat rootzone decreased significantly, from 4.7 to 1.9 wt.% and from 1.1 to 0.38 wt.%, respectively. In contrast, no significant decrease was observed in the non-rootzone, likely due to lower $CO_2$ partial pressure, organic acid release, and elemental uptake. The percentages of decrease to input in the rootzone were 58.8% for bytownite, 65.1% for pyroxene, and 25.6% for labradorite, reflecting higher dissolution rates of bytownite and pyroxene. Alongside these decreases, kaolin [$Al_2Si_2O_5(OH)_4$], a weathering product of plagioclase, increased significantly, and its increase correlated significantly ($r = 0.84$) with the decrease in plagioclase. As no carbonate minerals increased and $HCO_3^-$ showed an increasing trend ($p < 0.10$) relative to the control, we considered that basaltic mineral weathering primarily consumed $CO_2$ to produce $HCO_3^-$ rather than forming pedogenic carbonates under Japan's high-precipitation and acidic soil conditions. In conclusion, we successfully detected, for the first time, actual weathering of basaltic minerals applied to cropland, enabling quantitative verification of mineral weathering under field conditions.

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# Pedogenic Carbonates and Calcimetry Near Detection Limits: Field-scale weathering dynamics in wollastonite-amended clayey/acidic soils

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**ABSTRACT**

Enhanced Rock Weathering (ERW) is increasingly evaluated through alkalinity generation and bicarbonate export, yet in field systems dominated by rapid carbonate cycling, solid-phase pedogenic carbonates may offer a conservative and measurable proxy for carbon dioxide removal (CDR). In this study, we applied wollastonite, a highly reactive calcium silicate mineral, to cropland soils in the Port Colborne area of Southwestern Ontario, classified as Humic Luvic Gleysols (Jeddo series), developed in reddish-hued lacustrine clay with poor to imperfect drainage, clay loam textures, and moderately acidic pH (~6.2–6.5) (Kingston and Presant, 1989). These soils are typically considered marginal for carbonate formation due to high bulk density and seasonal water saturation, yet pedogenic carbonates are consistently observed following wollastonite amendment (Araujo and Santos, 2025).

For the first time, we conducted monthly measurements of soil pH and calcimetry over a full growing season, enabling resolution of short-term carbonate precipitation and re-dissolution dynamics. Despite carbonate concentrations near the detection limits of calcimetry, we observed statistically significant pH increases (~+1.0 unit) and measurable carbonate fluxes ($\Sigma\Delta CCE/\Delta t$), confirming that wollastonite can induce carbonate formation even under conditions not typically considered favorable for precipitation. These results build on prior validation of calcimetry for ERW monitoring (Silva et al., 2024), and demonstrate its sensitivity in marginal soil contexts. We hypothesize that localized microenvironments near silicate particles may exhibit elevated pH, enabling carbonate formation not predicted by bulk soil chemistry, a mechanism supported by prior column studies (Khalidy et al., 2023).

Rainfall was found to modulate carbonate formation, with cumulative precipitation over the preceding 7–10 days enhancing fluxes up to a saturation threshold (~30 mm), while dissolution fluxes remained largely independent of rainfall. This study also represents our first direct observation of carbonate cycling in the field, and provides a more dynamic view of ERW behavior than previous trials (Khalidy et al., 2025). By comparing calcimetry-derived fluxes with kinetic dissolution models and prior field studies, we help close the gap between theoretical weathering rates and those observed under real agronomic conditions. These findings support the integration of solid-phase carbon tracking into MRV frameworks and broaden the applicability of ERW monitoring approaches in temperate agroecosystems.

**Acknowledgments**

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# Reframing Carbon Accounting in Enhanced Rock Weathering: Counterfactuals, stoichiometry, and MRV implications

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## ABSTRACT

Enhanced Rock Weathering (ERW) is increasingly positioned as a scalable carbon dioxide removal (CDR) strategy, yet its credibility depends on reconciling idealized stoichiometric assumptions with field-scale realities. This perspective introduces a geochemically grounded accounting framework that integrates counterfactual scenarios and proposes a conservative baseline of one mole of $CO_2$ removed per mole of alkaline earth metal (AEM) weathered. While ERW is often modeled with a 2:1 molar ratio of $CO_2$ removal per mole of Ca or Mg (Beerling et al., 2020; 2025), this ideal assumes complete weathering, uninterrupted alkalinity transport, and permanent ocean storage. Field evidence and geochemical modeling show that these assumptions are frequently unmet due to acidic soil conditions, carbonate precipitation, and degassing during hydrological transit (Renforth and Henderson, 2017; Holden et al., 2024).

By considering counterfactuals such as carbonate liming and natural carbonate weathering, the net climate benefit of ERW is reframed. Silicate weathering often displaces processes that would otherwise release $CO_2$, such as acid-driven carbonate dissolution (Hamilton et al., 2007; Kaushal et al., 2013; Müller et al., 2020; Khalidy et al., 2022), thereby preserving native or added carbonates. This preservation, termed Natural Carbonate Protection (NCP), complements direct CDR and contributes to the total climate benefit. A stoichiometric model is presented to partition climate benefits into CDR and NCP, showing that the sum remains two moles of $CO_2$ per mole of AEM, but that only one mole should be credited as CDR under typical field conditions.

This reframing has implications for Monitoring, Reporting, and Verification (MRV). A 1:1 baseline simplifies MRV by focusing on direct indicators of weathering, such as cation flux, rather than requiring full tracking of bicarbonate fate. Projects may scale toward higher ratios only with robust evidence of carbonic acid-driven weathering, negligible counterfactual alkalinity, and demonstrated permanence. This tiered approach supports scalable, credible ERW deployment while maintaining scientific integrity and market confidence.

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# Subsurface and surface transport of crushed basalt

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**ABSTRACT**

Carbon Dioxide Removal (CDR), which removes $CO_2$ from the atmosphere, has been considered as a mitigation measure for global warming. One CDR method is the enhanced weathering of easily weathered rocks in soil. When crushed basalt is mixed with soil, the reaction of basalt with $CO_2$ in the air phase produces the bicarbonate. Either by entering groundwater as percolating water or by forming carbonates due to drying, $CO_2$ is fixed in the vadose zone. Finely crushed basalt is better for this purpose because it has a higher specific surface area. However, it is well known that fine mineral particles tend to move with flowing water. There was almost no information on the migration of incorporated fine basalt particles in soil. In this study, we conducted a preliminary experiments to examine the transport of crushed basalt particles through and above the soil.

Column percolation experiment and simulated rainfall experiment with a soil box were conducted. In the column experiment, two types of basalt mixing were carried out: one mixed basalt into the entire 25 cm layer, and the other mixed it into only the top 10 cm layer. Pure water was applied at 15 mm per day for 30 days. During the percolation, drainage from the column was periodically sampled, and cation and anion concentrations were analyzed. After the 30-day percolation, the soil column was sectioned into 1-5 cm layers, and the basalt content in each layer was measured. For the rainfall experiment, soil was packed into a 20 cm x 50 cm box with a 4 cm soil thickness. A 60 mm $h^{-1}$ simulated rainfall was applied for 60 min. During the rainfall, discharged sediments were sampled periodically, and after the rainfall, basalt contents of the surface soil were measured. Quantification of basalt in soil and sediment samples was conducted using X-ray powder diffraction (XRPD) by a method reported by Kurokawa et al. (2024). Andisol and Kunigami mahji soil (Hapludalt) were used. Basalt was crushed to a particle size < 0.1 mm. Basalt was applied at 10% or 20% by mass to the entire soil.

Results of column experiments with two different mixing depths suggested that the applied crushed basalt decreased due to reaction with $CO_2$ and other acids in soil, but the basalt itself did not move through the soil. Weathering of the basalt estimated from discharged cations and inorganic carbon was smaller than that estimated from XRPD analysis. Rainfall experiments showed that sediment discharge increased with increasing applied basalt. This is consistent with the understanding that areas with a higher fine-sand content are more susceptible to water erosion. Due to the sediment discharge from the box with a short slope length, the basalt content of the soil at the upstream decreased. This result suggests that topography should be considered when spreading basalt in situ and when assessing the amount of weathering of incorporated basalt.

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# Reframing Soil Carbon Stabilization: The Reactive Mineral Sink (RMS) Model and Its Synergy with Enhanced Mineral Weathering

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**ABSTRACT**

Reactive primary and secondary minerals play a pivotal yet underrecognized role in the transformation and stabilization of organic matter (OM) in soils. To address this gap, we introduce the Reactive Mineral Sink (RMS) model[1], which conceptualizes the key mechanisms through which reactive minerals govern the bioprocessing, transformation, transport, and long-term stabilization of OM. The RMS model encompasses three interconnected pathways. Biologically, reactive minerals modulate enzymatic and microbial processing of OM by binding extracellular enzymes and shaping microbial community structure and function. Chemically, they facilitate OM stabilization through adsorption and coprecipitation while simultaneously catalyzing OM transformation via surface-mediated reactions, including redox processes and mineral-induced catalysis. Physically, reactive minerals influence soil architecture - modifying aggregation, porosity, and hydrological flow paths - which in turn regulates OM transport, accessibility, and persistence.

The RMS framework provides an important and emerging insights for enhanced mineral weathering (EMW) as a soil carbon sequestration strategy. EMW accelerates the dissolution of silicate minerals, generating new reactive mineral surfaces and secondary weathering products that expand the mineral-associated organic carbon pool. By supplying fresh reactive phases and altering soil geochemistry, EMW reinforces all three RMS pathways: it stimulates microbial and enzymatic activity through nutrient release, increases chemical sorption and coprecipitation capacities, and promotes structural changes that stabilize carbon physically.

Together, the RMS model provides a comprehensive lens for understanding how reactive minerals regulate OM dynamics and soil carbon sequestration. It also highlights opportunities to restore soil biogeochemical function and enhance ecological resilience. We advocate for management strategies grounded in the RMS framework—including EMW-based approaches—to maximize organic carbon retention in soils, rejuvenate soil health, and contribute meaningfully to $CO_2$ mitigation.

***Keywords:*** Reactive minerals; Soil organic matter; Transformation; Stabilization; Conceptual framework; Enhanced mineral weathering

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# Impact of Enhanced Silicate Rock Weathering on Soil $CO_2$ Dynamics in Agricultural Field: Field Monitoring and Numerical Simulation

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## ABSTRACT

Enhanced rock weathering (ERW) has been proposed as an effective $CO_2$ sequestration strategy in agricultural systems through the application of crushed silicate rock powders. However, its effects on soil physical properties and $CO_2$ dynamics remain poorly understood, particularly under field conditions, where soil structure and moisture dynamics play critical roles in regulating gas exchange. Based on two years of field monitoring in the same farmland where crushed basalt powders were applied, the continuous impact of basalt application on soil physical properties and $CO_2$ dynamics was investigated. Field monitoring was conducted at an agricultural field with gray lowland soil at Hokkaido University, Japan (43.07° N, 141.34° E) during the 2023 (soybean, Glycine max) and 2024 (feed maize, Zea mays) growing seasons. Continuous measurements of soil $CO_2$, $O_2$, moisture, EC, temperature, and water potential were taken at depths of 10, 25, and 40 cm under four treatment regimes: Basalt–No Crop (BNC), Basalt–Crop (BC), No Basalt–Crop (NBC), and No Basalt–No Crop (NBNC; only in 2024). HYDRUS-HP1, which couples the Hydrus-1D model with the PHREEQC geochemical code, was tested for simulating soil water, temperature, and $CO_2$ behavior under silicate rock powder applications.

Measurements of soil physical properties showed an increase in dry bulk density, resulting in reduced total porosity in the BC and BNC plots. This change was attributed to pore clogging by the applied rock powder. In addition, the measured water retention curves exhibited enhanced water retention in the basalt-treated plots. In 2023, soil $CO_2$ concentrations at 10 cm depth were significantly higher in the BC plots compared to the NBC plots. The estimated net $CO_2$ production rate at 10 cm depth was also greater in the BC plot than in the NBC plot. In 2024, although the difference in $CO_2$ production rate between the basalt-treated and untreated plots was smaller than that observed in 2023, the cumulative $CO_2$ production rate remained higher in the basalt-treated plots. An increase in soil pH was observed in the basalt-treated plots, likely due to mineral weathering. Therefore, further investigation is needed to clarify how changes in soil pH influence the rate of organic matter decomposition (i.e., $CO_2$ production rate). Numerical simulations that incorporated basalt weathering successfully reproduced the observed soil moisture, temperature, and $CO_2$ dynamics with high accuracy. In the future, sensitivity analyses of environmental factors such as air temperature, rainfall patterns, and soil organic matter content on soil $CO_2$ dynamics and carbon sequestration will be conducted.

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# Can Silicate Rock Powder Replace Agricultural Lime and Sequester Carbon in Acid Soils? – Field and Lab Studies

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**ABSTRACT**

Powdered silicate rocks added to acid soils may remove atmospheric carbon dioxide by forming bicarbonates ($HCO_3^-$) eventually stored in oceans. A 10-ha farm-scale study with reduced-tillage in Maryland, USA, with Ultisols (initial $pH_w$ 5.7-6.0) formed from shale or limestone was begun October 2023 when we applied metabasalt powder at 17 and 34 Mg/ha (1x and 2x the rate modeled to raise soil pH equivalent to the recommended limestone), 3.4 Mg/ha limestone, and an unamended control. Wheat was planted in late October 2023, followed by soybeans planted in July 2024, a wheat cover crop in October 2024, and maize in June 2025. We periodically sampled soils from 0-10, 10-20, and 20-30 cm depths, and macropore water at 60 and 90 cm (by suction lysimeters). We measured pH (in water, 0.01*M* $CaCl_2$, and 1*M* KCl ), electrical conductivity (EC), dissolved $HCO_3^-$, and magnesium. We sampled winter wheat leaves in May, wheat grain in July, and soybean foliage in August 2024.

We conducted an aerobic lab incubation of limestone, olivine, and metabasalt powders mixed with high soil organic matter (SOM) topsoil (0-10 cm) or low SOM subsoil (20-30 cm) from four soils (initial $pH_{water}$ 4.6 to 5.6), ranging from loamy sand to silty clay loam kept at 20 ºC and 50-60% water-filled pore space. After 0, 30, 90, and 240 days, soils were mixed 2:1 soil:water, and the EC, $pH_{water}$,$pH_{CaCl2}$, $pH_{KCl}$ , and dissolved $HCO_3^-$, in the suspension were measured.

In the field study, by early April 2024, the pH of 0-10 cm soils treated with limestone was significantly higher than in the control and 17 Mg/ha metabasalt. The 34 Mg/ha metabasalt soil pH was intermediate. After 18 months, only limestone treatment had significantly higher pH than the control. No treatment effects were detected below 10 cm. Soil $pH_{CaCl2}$ and $pH_{KCl}$ were less variable than $pH_{water}$. Soil EC fluctuated with time and soil depth, but was elevated in limestone plots. There were no differences in the porewater $HCO_3^-$ among rock treatments. No treatment effects were observed on elemental concentrations in any plant samples.

During the incubation study, EC increased from < 100 mS/cm to > 500 mS/cm in the topsoils, but only from 50 to 100 mS/cm in the subsoils, suggesting SOM mineralization dominated over rock powder weathering. Mean $pH_{CaCl2}$ of unamended topsoils declined from 4.5 to 4.0, while rising to 4.6, 5.4, and 6.8 in the topsoils amended with metabasalt, olivine, and limestone, respectively. In the subsoils, $pH_{CaCl2}$ reached levels of 6.2, 6.5, and 7.3, respectively, suggesting less buffering with lower SOM. After 90 days of incubation, $HCO_3^-$ averaged 2.2, 7.3, 10.5, and 10.6 mg/L for the soils amended with no rock, metabasalt, olivine, and limestone, respectively. Thus, both silicate rocks dramatically increased $HCO_3^-$ in the static incubation, but no increase was detected in the field leaching water sampled from metabasalt plots.

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# Column experiment and numerical simulation for quantification of carbon fixation by enhanced rock weathering

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**ABSTRACT**

Enhanced rock weathering (ERW) is a promising carbon dioxide removal technology by silicate mineral dissolution with $CO_2$. Though numerous laboratory and field trials have been conducted to assess the effectiveness of ERW, accurate quantification of carbon fixation remains challenging. The common approach estimates carbon sequestration from the concentrations of cation released by basaltic mineral dissolution (mainly Ca and Mg). However, this method must account for mineral weathering caused by other acids present in soil, such as nitrates, sulfates, and organic acids. Alternatively, bicarbonate leaching will provide a direct indicator of carbon fixation by ERW, but its application in field condition is difficult because bicarbonate is not conservative after sampling.

To compare these quantification methods, we conducted controlled column experiments and numerical simulations. The acid red soil from Okinawa Prefecture, Japan was used. The soil pH (1:5 H2O) was 5.6. The basalt powder was composed mainly Ca-plagioclase (60%) and median diameter was 66 μm. The soil and basalt were mixed with 10:1 mass ratio and packed into a cylindrical column at 25 cm in height. Pure water was supplied at 15 mm/day for one month (total 450 mm), and effluents at the bottom were sampled. pH, EC, major cations (Na, K, Ca, Mg), anions (Cl, nitrate and sulfate) and total inorganic carbon in the effluents were analyzed. After the leaching experiment, the dissolution of Ca-plagioclase was evaluated by the X-ray powder diffraction. Experimental results were reproduced using a coupled HYDRUS-1D and PHREEQC (HP1) reactive transport model. Plagioclase dissolution was expressed as the first-order reaction proportional to mineral surface area.

Bicarbonate concentrations in the effluents were approximately 100 times higher than those expected from equilibrium with the soil $CO_2$ concentration in the column (0.1%), showing great enhancement of $CO_2$ leaching by ERW. However, most of anions in the effluents were chloride and sulfate, suggesting that weak carbonic acid was not dominant proton source for silicate dissolution in this acidic soil environment. XRD analysis showed that 57% of the added Ca-plagioclase had dissolved, whereas Na-plagioclase which originally contained in the soil remained unchanged, consistent with the dissolution kinetics of plagioclase minerals (Ca>>Na).

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# Reconnecting geology and soil science for a broader One Health framework: Insights from Enhanced Rock Weathering

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**ABSTRACT**

Soil science and geology, once intertwined, have long evolved in isolation and remain largely disconnected in Japan to this day. Although the Fukushima nuclear accident drew geochemists' attention to soil mineralogy—particularly the specific adsorption mechanisms of radiocesium on 2:1 clay minerals—most soil scientists have rarely crossed disciplinary boundaries to engage with geology. Enhanced rock weathering (ERW) offers a unique opportunity to bridge this gap, fostering collaboration between these historically separated fields.

In 2022, the new project "Advanced enhanced rock weathering technology development (A-ERW)" funded by New Energy and Industrial Technology Development Organization (NEDO), Japan, was launched. The project encompasses multi-site field experiments to investigate the effect of basalt powder amendment on soil fertility, plant nutrition, and carbon budget. We applied same basalt to the top soil at a mixing ratio of 10 wt% across eight sites: three rice fields, two soybean fields, one sugarcane field, one buckwheat field and one sugar beet field, all subjected to continuous cultivation trials for two to three years.

Soil pH increased consistently by 0.5-1.0 unit after amendment and remained higher than control plots throughout the experiments. Significant weathering of minerals in basalt powder, i.e., Ca-rich feldspars (bytownite and labradorite) and pyroxenes (diopside), was confirmed using quantitative X-ray diffraction method in several research sites. Net negative carbon emission relative to control plots was observed in soybean fields, based on $CO_2$ flux monitoring (chamber method) and soil sensors. Increased availability of basalt-derived nutrients (e.g., Si and Mg) and corresponding improvements in crop performance, including increase in yield or better nutrient balances, were evident especially for *Poaceae* crops such as rice and sugarcane, whereas no significant adverse effect was observed in other crops examined.

Thus, a single basalt amendment can modify soil mineralogy and provide multiple benefits for soil rejuvenation, including acid neutralization, greenhouse gas mitigation, and improving nutrient status. Since the Green Revolution, modern agriculture relies heavily on chemical fertilizers containing nitrogen, phosphorus, and potassium. Supply of rock-derived micro- and macro-nutrients has long been dismissed in the fertilization strategies. Exploring the nexus between geomaterial weathering, carbon cycling, and nutrient dynamics represents a new challenge for soil science, paving the way for a broader One Health framework that includes geology.

**Key words:** Carbon sequestration, Interdisciplinarity, Remineralization, X-ray powder diffraction analysis

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# Exploring Basalt Weathering for Mitigating Greenhouse Gas Emissions in Rice Paddy System

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**ABSTRACT**

Among carbon dioxide removal (CDR) technologies, the enhanced rock weathering (ERW) using finely ground basalt to farmlands has emerged as a promising nature-based solution that can both improve soil health and reduce $CO_2$ emissions. Despite its application across diverse farmland systems, the efficiency of ERW under flooded conditions remains poorly understood. Rice paddy system is one of the major sources of anthropogenic methane ($CH_4$); therefore, any increase in $CH_4$ emission following basalt application could offset the $CO_2$-based CDR potential of ERW. Thus, this study aimed to quantify the impacts of ERW on carbon dioxide ($CO_2$), $CH_4$, and nitrous oxide ($N_2O$) emissions from paddy soils. A field experiment was conducted on Fluvisols in Kyoto in Japan in 2025 comparing a control plot and a basalt-amended plot (200 ton $ha^{-1}$) in triplicate. GHG fluxes were collected biweekly using the closed-chamber method. The results indicated that basalt amendment reduced $CO_2$ and $CH_4$ flux by about 20% and 10%, respectively, decreasing cumulative emissions of $CO_2$ and $CH_4$ by totally 0.58 t C $ha^{-1}$ during the five months of growing season, while $N_2O$ fluxes remained near detection limits. Nevertheless, the reductions of basalt-amended and control plots had no statistical significance. Although greenhouse gas fluxes significantly correlated with soil temperature, moisture, and Eh, these variables showed limited difference between treatments. In contrast, basalt amendment consistently increased soil pH by an average of 0.2 units relative to the control, with the difference becoming more pronounced during drainage periods. Although basalt amendment increased soil pH and reduced seasonal $CO_2$ and $CH_4$ emissions, the available field measurements were insufficient to identify the underlying mechanism. Thus, the biogeochemical pathways responsible for these changes cannot yet be resolved from the present dataset. This study provides the first field evidence of ERW potential in GHG mitigation in rice paddy systems. Future studies should incorporate measurements which can directly reflect biogeochemical dynamics. Furthermore, comparative analyses across climatic zones will be essential to determine whether the biogeochemical mechanism proposed in this study is consistent across paddy systems under different climatic conditions.

**Key words:** nature-based solution, paddy soils, carbon sequestration

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# Impact of soybean cultivation on basalt weathering in agricultural system

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**ABSTRACT**

Enhanced Rock Weathering (ERW), using mafic rock powder (e.g., basalt) on agricultural land, is a carbon dioxide removal (CDR) strategy that offers the co-benefits of increasing soil pH and supplying essential elements like magnesium (Mg) and calcium (Ca). Additionally, plant promote mineral weathering in the rhizosphere, but there is few research on enhancement effect in rhizosphere on silicate mineral weathering in ERW application. This study investigated the reciprocal interactions between basalt powder application and soybean (*Glycine max* (L.) Merr.) growth in both pot and field experiments. In the pot experiment, soybean was cultivated in 3 kg of soil (gray lowland soil) for 118 days. Treatments included basalt treatments at 5, 10, and 20 wt.% (BA5, 10, 20), lime treatments (Lime5, 10, 20) matching the pH increase of BA treatments, and no application (Control). Planted and unplanted treatments were established for Control and BA treatments. At maturity (R8), shoot dry weight and element concentrations were measured. Soil was thoroughly mixed and sampled before planting and after harvest, and analyzed for soil pH and exchangeable cations (Ex-cations). The mineral weathering was quantified as ΔCa (or ΔMg), calculated as the sum of total Ex-Ca (or Ex-Mg) and total plant uptake at R8, minus the initial total Ex-Ca (or Ex-Mg). The field experiment included basalt plots (75, 150, 300 t $ha^{-1}$, equivalent to BA5, 10, 20), one lime plot (1.5 t $ha^{-1}$), and Control plot, all with planted and unplanted plots. Soil and plant samples were collected throughout the growing season and analyzed for the same parameters, with soil mineral composition assessed using X-ray Powder Diffraction (XRPD). Both experiments showed that basalt application increased soil pH and Ex-Mg, while lime application increased soil pH and Ex-Ca. Regarding soybean growth, significantly higher shoot dry weight was observed only in BA10 and BA20 compared to Control in the pot experiment, but no significant difference in the field experiment. The growth promotion in the pot experiment was correlated with Ex-Mg but not soil pH, and the limited soil volume led to lower post-harvest Ex-Mg levels compared to the field, both of which imply that the Mg supply from basalt was beneficial under these relatively low available Mg conditions. Indicators of mineral weathering showed a significant positive root enhancement effect: In the pot experiment, ΔMg was higher in planted treatments than in unplanted treatments. In the field experiment, the content of pyroxene (a major basalt mineral) in the soil was significantly lower in planted plots compared to unplanted plots in BA20. This root-enhanced weathering indicates a positive feedback loop that can accelerate CDR and nutrient supply in ERW application.

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# Wollastonite reshapes soil organic carbon fraction dynamics and enhances carbon sequestration potential

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## ABSTRACT

Enhanced rock weathering (ERW) is a promising strategy for atmospheric $CO_2$ sequestration, but its impacts on soil organic carbon (SOC) fractionation and stabilization remain poorly understood. This study investigated how wollastonite application influences SOC dynamics in a three-month soybean pot experiment. In surface soils, the apparent SOC decline following wollastonite addition was primarily a dilution effect, not true carbon loss. Nevertheless, wollastonite significantly restructured SOC fractions and microbial activity, weakening organo-mineral associations (mineral-associated organic carbon reduced by 5%-10%), reducing microbial $CO_2$ assimilation (RubisCO carbon-fixing genes cbbL and cbbM decreased by 49%-90%), weakening macroaggregate protection (water-stable aggregate stability index reduced by 4%-6%), and enhancing SOC mineralization (easily oxidized organic carbon decreased by 18%-24%). In contrast, deeper soils exhibited increased SOC stabilization and accumulation (mineral-associated organic carbon increased by 5%-10%). Across the 0-30 cm profile, wollastonite application increased both organic and inorganic carbon pools, producing a net gain of 3.7-4.1 $Mg \cdot ha^{-1}$ in total carbon stocks. Soybean presence had little effect on net SOC storage but altered fractionation, stimulating dissolved organic carbon accumulation and easily oxidized organic carbon mineralization, while contributing less to particulate organic carbon formation. Collectively, these findings reveal that ERW did not uniformly enhance SOC storage but rather redistributed SOC fractions, reducing stability near the surface while promoting stabilization at depth. This study provides experimental evidence that ERW outcomes are strongly depth-dependent and regulated by soil–plant–mineral interactions, underscoring the importance of SOC fraction dynamics in assessing its long-term climate-mitigation potential.

**Acknowledgments**

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# The Impact of Enhanced Rock Weathering on Soil Carbon Dynamics: A Global Meta-Analysis of Environmental and Soil Factors

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**ABSTRACT**

Enhanced rock weathering (ERW) is a promising, scalable pathway for carbon dioxide removal (CDR), but its net soil-system benefits and governing mechanisms remain debated. This study synthesized empirical studies from January 2014 to June 2025, assembling a database spanning rock properties ($SiO_2$ content, dosage, particle size), soil factors (initial pH, clay content), and experimental conditions (field/pot, planted/unplanted, duration). Overall effects were quantified using weighted random-effects models with bootstrap confidence intervals. Boosted regression trees (BRT) were used to identify dominant drivers. Results indicate that ERW produced a measurable net carbon sink at the ecosystem scale, with an average CDR of 3.5 t $CO_2$ $ha^{-1}$ $yr^{-1}$ and an increase in total soil carbon (TC) of 2.1%. Within carbon pools, dissolved inorganic carbon (DIC) increased most (+273.5%), followed by soil inorganic carbon (SIC; +187.9%). Soil organic carbon (SOC) and microbial biomass carbon (MBC) increased by 3.6% and 23.3%, respectively, while dissolved organic carbon (DOC) and soil $CO_2$ flux showed no overall change. Methane emissions declined by 30.5%, which further enhanced ERW's net climate benefit. Design and context modulated outcomes. Each additional 1 t $ha^{-1}$ of rock raised CDR by approximately 20 kg $CO_2$ $ha^{-1}$ $yr^{-1}$; fine powder (<2 mm) achieved about 6 times the CDR of coarse powder (>2 mm). Higher initial soil pH strengthened CDR (+183 kg $CO_2$ $ha^{-1}yr^{-1}$ per 0.1 pH unit); whereas acidic and low-clay soils favored SOC accumulation. SOC often declined in the short term but increased over longer durations; while SIC gains diminished over time. Methodologically, pot studies overestimated SIC gains by approximately sevenfold relative to field studies and underestimated SOC stabilization. BRT results attributed CDR and TC mainly to soil factors (pH, clay content), whereas SOC and SIC were governed primarily by rock properties ($SiO_2$, particle size, dosage). In summary, ERW delivers net soil-system carbon sequestration, jointly regulated by soil, rock, and design. Practically, a "fine powder-low-to-medium dosage-matched soil background" strategy is recommended. Integrating methane (and where relevant, nitrous oxide) into $CO_2$-equivalent accounting, together with long-term field monitoring and cost-risk assessments, is essential forcredible, scalable deployment.

# Enhanced weathering using blast furnace slag(BFS) for carbon sequestration in soil

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**ABSTRACT**

As climate change intensifies globally, the importance of Carbon Dioxide Removal (CDR) technologies has become increasingly critical. The Intergovernmental Panel on Climate Change (IPCC) suggested ten priority CDR technologies, including Enhanced Weathering (EW). EW technology accelerates natural weathering processes by grinding and applying silicate minerals such as basalt and olivine or industrial byproducts rich in calcium (Ca) or magnesium (Mg) to soils, thereby sequestering atmospheric $CO_2$ in the form of stable inorganic carbon. However, South Korea faces constraints in implementing EW technology due to limited domestic reserves of silicate minerals such as basalt and olivine. Consequently, this study utilized blast furnace slag (BFS), an steel industry byproduct characterized by high Ca content and alkaline properties (pH: 8.9), as an EW feedstock material. Following assessment of the CDR potential (CDRpot) of BFS, field trials were conducted on agricultural soils at Kangwon National University's experimental farm to evaluate carbon sequestration capacity, change in soil properties changes, and impacts on maize (*Zea mays*) productivity. Results demonstrated that soil exchangeable Ca, available phosphorus (Av.$P_2O_5$), available silicon, and cation exchange capacity (CEC) increased relative to controls in proportion to BFS application rates, with higher values observed in fine-particle treatments compared to original-particle applications. Maize grain yields generally increased compared to controls; however, fine-particle treatments exhibited reduced yields in certain plots due to poor drainage conditions. CDRpot values for coarse-particle treatments at 2 and 10 t $ha^{-1}$ were 0.08 and 3.17 $CO_2$-t $ha^{-1}$, respectively, while fine-particle treatments at equivalent rates yielded 1.45 and 4.39 $CO_2$-t $ha^{-1}$, respectively. These results indicate that increased surface area accelerates weathering reactions. As this represents a single-year field trial, long-term reapplication studies are necessary to accumulate additional data on sustained carbon sequestration efficacy and soil health dynamics. Furthermore, $CO_2$ emissions from grinding processes for fine-particle production must be incorporated into CDRpot calculations to ensure accurate life cycle assessments.

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# Mechanisms of Carbon Sequestration through Bacillus-Enhanced Basalt Weathering on the Soil Priming Effect

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**ABSTRACT**

The continuous rise in global atmospheric carbon dioxide ($CO_2$) concentrations has led to a significant increase in carbon output through the priming effect of soil microbial respiration, thereby limiting soil carbon sink capacity. Enhanced rock weathering represents a promising strategy for $CO_2$ removal, which can promote the conversion of $CO_2$ released by the priming effect into $HCO_3^-$, ultimately forming inorganic carbon to stabilize the soil carbon pool. This study investigates how the combined application of basalt and Bacillus subtilis, mediated by the soil priming effect, influences the turnover of the soil carbon pool. Over a 28-day incubation period, we added Bacillus subtilis, basalt, and $^{13}C$-labeled glucose solution to the soil, and systematically analyzed soil respiration, glucose mineralization, priming effect, carbon pool content, as well as changes in soil physicochemical properties and carbon particle morphology. The results showed that Bacillus subtilis accelerated soil respiration, while basalt weathering suppressed cumulative $CO_2$ release, with the inhibitory effect strengthening over time. Additionally, basalt significantly reduced cumulative glucose mineralization and altered the direction of the priming effect. The combined application of basalt and Bacillus subtilis notably increased soil organic carbon and inorganic carbon content, with organic carbon rising by up to 24.07%. The net soil carbon fixation reached 595.86 $\mu g \cdot C \cdot g^{-1}$, enhancing the stability of the soil carbon pool. The soil priming effect, mediated by microorganisms, intensified basalt weathering, accelerated proton neutralization in the soil, increased bicarbonate alkalinity, raised soil pH, effectively ameliorated acidic conditions, and released soluble $Ca^{2+}$ and $Mg^{2+}$ ions. These findings indicate that microbially enhanced basalt weathering, driven by the soil priming effect, significantly improves soil carbon sink potential and mitigates soil acidification through mechanisms such as inhibiting substrate mineralization, accelerating inorganic carbon fixation, and increasing mineral-associated organic carbon content.

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# Second-year effects of basalt application on maize growth and soil carbon sequestration under field conditions.

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## ABSTRACT

[**Background]** Enhanced Rock Weathering (ERW) is a climate mitigation strategy that accelerates natural rock weathering processes to sequester atmospheric carbon dioxide. In agricultural fields, the application of crushed basalt to soil is expected to release base cations ($Ca^{2+}$, $Mg^{2+}$) through weathering processes. These cations can react with carbonate ions in the soil solution, resulting in the formation of relatively stable carbonate minerals. Bicarbonate ions generated during these reactions may be leached and contribute to carbon sequestration in the ocean. In addition, elements released during basalt weathering can serve as nutrients for crops, providing co-benefits such as enhanced growth, increased yields, and improved crop quality. To implement ERW technology in the field, it is necessary to evaluate the persistence of its effects following basalt application. This study aimed to elucidate the effects of basalt application on maize (*Zea mays* L.) growth and soil carbon sequestration, with a particular focus on elemental dynamics.

**[Methods]** Field experiments were conducted in 2024 using maize (Zea mays L., cv. P9027) at an experimental field of Hokkaido University (43.07° N, 141.34° E; gray lowland soil). To evaluate the residual (second year) effects of ERW, the study utilized plots that had received a one-time application of crushed basalt (particle size: <100 μm) in 2023, followed by a soybean crop. Five treatments were arranged in a randomized design with three replications: a control (no application), three basalt application rates (5, 10, and 20 wt.% incorporated into the top 15 cm; hereafter BA5, BA10, and BA20), and a lime application (0.15 wt.%). While basalt was applied only in 2023, lime was reapplied in 2024 to match the soil pH of BA10. Soil and plant samples were collected at the vegetative (V9), reproductive (R1), and harvest (R6) stages. For plant analyses, dry weight, elemental concentrations, and grain yield were determined. Soil analyses included pH, exchangeable cations, available silicon (Si), inorganic carbon concentrations, and mineralogical composition determined by X-ray powder diffraction (XRPD). Additionally, the total carbon budget was calculated based on integrated plant and soil data.

**[Result]** Soil pH increased similarly in both basalt and lime treatments across all growth stages. However, basalt application tended to enhance maize dry weight and grain yield compared to the control, with BA20 showing a significant increase in leaf dry weight at R1. In basalt treatments, soil exchangeable magnesium (Mg) at V9 and R1, and plant Mg concentrations at R6, significantly increased. Furthermore, soil exchangeable Mg was significantly and positively correlated with shoot dry weight at R1 and R6. Soil available Si also significantly increased with basalt application. While plant Si concentrations showed an increasing trend in basalt treatments, they were significantly lower in the lime treatment than in the control, BA5, and BA10. Soil exchangeable calcium (Ca) concentrations were significantly higher in the lime treatment at V9 and R1, and plant Ca concentrations also tended to be higher. Although basalt contains Ca, soil exchangeable Ca remained unchanged, likely due to high initial soil Ca levels. These results suggest that basalt-induced growth promotion may not be solely attributable to pH changes but also to the supply of essential elements such as Mg and Si released through weathering. The influence of basalt application remained evident in the field two years after the initial treatment. The potential for soil carbon sequestration via ERW is currently under investigation.

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# Soil Re-engineering – A New Approach to Improve Crop Productivity on Constrained Sandy Soils in Water-Limited Environments in Western Australia

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## ABSTRACT

Western Australia (WA) produces high-quality grain crops under rainfed systems on some of the world's oldest, infertile sandy soils. Nearly two-thirds of WA's cropping land is constrained by soil compaction, acidity, poor fertility, and low water-holding capacity. While deep tillage with lime and clay can alleviate these issues, the full productivity potential from their complete removal remains unclear.

We used a "*soil profile re-engineering*" approach — involving removal and replacement of soil horizons with uniform mixing plus lime, clay, and inorganic and organic nutrient incorporation — to simulate the maximum benefits of deep soil amelioration (Azam, 2025). We then tested farm-scale experiments using conventional and novel machinery to assess the feasibility of adoption by the farmers. Our research addressed two key questions: (i) can the immediate improvements in soil health and productivity be sustained long-term, and (ii) can this approach be scaled for growers' adoption? To evaluate this, we conducted two long-term trials (Bolgart, a deep sand; Meenar, a sandy duplex) over five seasons and four grower-scale trials (Grass Valley, Mt Horner, Wagin and North Stirling) in 2025 season across WA.

In the long-term profile re-engineering trial at Bolgart site, some re-engineering treatments at least doubled grain yield and water-use efficiency (WUE) of five crop types compared to the untreated control, while the most effective treatment achieved the estimated water-limited yield potential (Yp) on both sites. Overall, yields increased by 66% following the removal of acidity and compaction. Deep incorporation of clay and organic matter enhanced yield and WUE on deep sand but not sandy duplex soils, whereas deep inorganic nutrient placement was more beneficial on sandy duplex soils. These improvements persisted for five seasons and are likely to last longer. Yield and WUE gains were associated with deeper, more continuous root growth, improving capture of water and nutrients otherwise unused in untreated subsoils.

Farm-scale re-engineering experiments using traditional and emerging machinery confirmed immediate mitigation of acidity and compaction and significant improvements in water-holding capacity. Grain yield and WUE increased by 4 t $ha^{-1}$ and 12 kg $mm^{-1}$, respectively, in the first season in the farm-scale trials compared to the controls.

Overall, our findings show that soil re-engineering can transform sandy soil into more resilient production systems, enabling consistent achievement of Yp at farm scale. Future research should explore the interaction of soil re-engineering to different depths with seasonal variability, crop rotations, and alternative soil management strategies to maximise its agronomic and economic benefits.

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# Combined Application of Straw and Biochar: A Synergistic Strategy to Enhance Fertilizer Efficiency, Boost Yield, and Reduce Greenhouse Gas Emissions in Northeast China

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**ABSTRACT**

Incorporating straw or biochar into soil is widely acknowledged for improving soil structure and nutrient content. However, applying large amounts without proper management may lead to negative effects, including increased greenhouse gas (GHG) emissions, imbalances in the soil carbon-to-nitrogen (C/N) ratio and inhibition of crop growth. Thus, careful management is essential to optimize benefits and minimize risks. A field experiment conducted in black soil region of Northeast China (2022 to 2023) to explore the effects of straw and biochar return methods along with varying N fertilizer on GHG emissions and soybean yield. This study investigated two straw and biochar return methods (36 t ha-1 full straw return, S; and conversion of 18 t ha-1 straw to biochar mixed with residual straw return, SB) along with three N fertilizer levels (72 kg N $ha^{-1}$, N1; 57.6 kg N $ha^{-1}$, N2; and 43.2 kg N $ha^{-1}$, N3). Additionally, the control treatment (CN1) applied conventional nitrogen fertilizer without straw or biochar. Results showed that the SBN combination produced a higher soybean yield with lower GHG emissions compared with the SN combination. This improvement was attributable to biochar-induced regulation of soil hydrothermal conditions, which enhanced soil moisture content by 7.68% and raised soil temperature by 0.78–2.14°C at key growth stages (seedling and maturity). Moreover, biochar significantly increased C and N sequestration, boosting soil total nitrogen by 8.35% and soil organic carbon by 38.97%. Specifically, the most effective treatment was the SBN2, which increased soybean yield by 16.88% and reduced greenhouse gas emission intensity (GHGI) by 42.37%. Structural equation modeling and regression analysis revealed that soil hydrothermal conditions and C and N sequestration were key factors driving both yield improvement and emission reductions. The results indicated that combining straw and biochar return with optimized N fertilizer input was effective in reducing GHG emissions and increasing grain yield. This approach offers a sustainable method for soybean production with lower nitrogen fertilizer inputs, providing valuable insights for agricultural practices in the black soil region of Northeast China.

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# Engineering Technology and Practice of Microbial-Synergized Organic Material Amelioration in Albic Soil

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## ABSTRACT

**Research Background and Scientific Basis**

Albic soil is a key soil type for grain production and is widely distributed across several countries. It is also a typical problematic soil in eastern China, covering approximately 5.27 million hectares, among which Heilongjiang Province accounts for about 3.31 million hectares—mainly located in the Sanjiang Plain, where it serves as the dominant arable soil type. However, Albic soil suffers from multiple severe constraints, including nutrient deficiency, strong acidity, compact physical structure, and especially low microbial activity, which severely restrict crop growth and result in low and unstable yields. These problems not only hinder local agricultural productivity but also threaten the sustainable development of cultivated land resources. Therefore, improving the productivity of Albic soil is of strategic importance for ensuring global food security.

Traditional fertilizer-dependent management systems have failed to reverse soil degradation effectively; excessive fertilization has instead intensified acidification and nutrient imbalance. Hence, restoring the fertility of Albic soil urgently requires an integrated regulatory strategy capable of improving its physical structure, chemical properties, and biological functions simultaneously. Organic waste recycling—particularly the application of crop straw, livestock manure, and biomass ash—offers a promising pathway to rebuild soil organic carbon pools and nutrient cycling capacity. Nevertheless, under cold environmental conditions, microbial activity is suppressed and straw decomposition is slow, limiting the effectiveness of such measures.

To address these limitations, this study focuses on integrating organic waste amendments with functional microbial inoculants to construct a synergistic soil fertility enhancement system tailored for Albic soil. By combining field trials with controlled-environment experiments, the study systematically elucidates the roles of organic residues and microbial communities in aggregate formation, enzyme activity regulation, nutrient transformation, and community assembly. The overarching goal is to establish a mechanistic framework for transforming Albic soil ecosystems from a state of "low fertility–high resistance" to "high activity–high stability–high nutrient efficiency."

**Experimental Framework and Methodology**

**1.Soil Type and Cropping System**

Field experiments were conducted in a typical Albic soil region under a soybean–maize rotation system. Complementary pot and microcosm experiments were designed under controlled conditions to explore microbial and biochemical mechanisms.

**2.Treatment Design**

Treatments included:(1) untreated control; (2) straw return; (3) straw return + composite microbial inoculant; (4) organic substitution for chemical fertilizer; (5) biochar inoculated with *Piriformospora indica*; (6) biomass ash combined with arbuscular mycorrhizal fungi (AMF) inoculation.

**3.Measured Parameters**

Soil physicochemical properties (pH, organic matter, total nitrogen, total phosphorus, available phosphorus), enzyme activities (urease, alkaline phosphatase, cellulase, β-glucosidase, laccase), and aggregate size distribution were determined. Microbial community structures were analyzed via 16S rRNA and ITS high-throughput sequencing, coupled with FUNGuild and FAPROTAX functional annotations. Co-occurrence network analysis, structural equation modeling (SEM), and redundancy analysis (RDA) were applied to reveal causal relationships between biological processes and soil fertility improvement.

**4. Metabolomics and X-ray Tomography**

Non-targeted metabolomics was employed to characterize root–microbe carbon flow, while X-ray CT scanning visualized changes in aggregate microstructure. Glomalin-related soil protein (GRSP) was quantified to assess the contribution of AMF to aggregate stability.

**Main Findings and Mechanistic Insights**

**1.Synergistic Effects of AMF and *Trichoderma longibrachiatum* under Straw Incorporation**

The synergistic role of AMF and *T. longibrachiatum* in promoting straw decomposition and nutrient release in Albic soil was systematically elucidated. Results indicated that *T. longibrachiatum* enhanced host root responsiveness to AMF, increasing mycorrhizal colonization rates and strengthening AMF-mediated regulation of *Trichoderma*'s ecological functions, shifting its role toward organic matter degradation. The co-inoculation significantly improved key decomposing enzyme activities and soil pH, ameliorating soil acidity and optimizing nutrient release and transformation conditions.

This accelerated straw decomposition and nutrient availability, thereby enhancing nutrient uptake efficiency and biomass accumulation in crops. Furthermore, AMF–*Trichoderma* interaction reshaped rhizosphere fungal community structures, enriched straw-decomposing taxa, and increased the abundance of *Sphingomonas* and other aerobic heterotrophs, thus altering the functional composition of the microbial community. The co-inoculation also markedly improved the soil quality index (SQI) of Albic soil.

Overall, the synergistic inoculation of AMF and *T. longibrachiatum* represents a promising biotechnological innovation capable of enhancing straw return efficiency and soil fertility, offering significant potential for ameliorating degraded Albic soil and optimizing straw resource utilization.

**2. Complementary Effects of Biochar and *Piriformospora indica* and Rhizosphere Metabolic Reconfiguration**

The combined regulation of crop–microbe interactions in Albic soil by biochar and P. *indica* was investigated through a metabolomic network approach. Results demonstrated that co-application significantly increased bacterial α-diversity and reshaped dominant genera such as *Bacillus* and *Lysobacter*. The synergistic treatment promoted root secretion of key metabolites including *isoleucine* and *isocitrate*.

These metabolites attracted *Lysobacter*, establishing a positive feedback loop between microbial populations and rhizosphere metabolites, which in turn modulated root exudation, stimulated root morphological development, and enhanced biomass accumulation (RPA, RSA, RV). Increases in *Bacillus* and *Lysobacter* abundances were strongly correlated with plant biomass, with isocitrate identified as a key metabolic driver in the biochar–*P. indica* synergy. Although confirmed under pot conditions, further field-scale validation is required to assess its agronomic applicability in Albic soil.

**3. Long-Term Effects of Organic Fertilizer Substitution**

Compared with conventional fertilization, partial replacement of chemical fertilizers with organic amendments significantly increased soil pH and nutrient levels. Under high substitution ratios, soil pH rose by approximately 4.33%, while organic matter (OM), total phosphorus (TP), available phosphorus (AP), and hydrolyzable nitrogen (HN) increased by 20–30%.

Bacterial diversity and abundance rose by more than 20%, whereas fungal diversity decreased correspondingly. The dominant phyla—Proteobacteria and Basidiomycota—increased by 36.11% and 286.79%, respectively. Soil pH and organic matter content were identified as key determinants of rhizosphere microbial community composition in soybean-grown Albic soil. Organic substitution also strengthened bacterial interactions, rendering the microbial network more complex and stable. These findings highlight the diverse responses of rhizosphere microbial communities to organic inputs and provide a scientific foundation for optimizing fertilization strategies and improving soil health in Albic soil regions.

**Integrated Analysis and Theoretical Implications**

Based on multi-year, multi-scale investigations, this study proposes a conceptual model of a microbe–organic matter synergistic regulation system for Albic soil restoration. The mechanism operates through three hierarchical layers:

**1. Biophysical Reconstruction Layer:** Organic wastes (straw, biochar, manure) provide structural and chemical support, alleviating compaction, enhancing porosity, and regulating acidity.

**2. Biochemical Activation Layer:** Functional microbes catalyze organic matter degradation, release nutrients, and form microbial residues that stabilize soil carbon.

**3. Bioecological Feedback Layer:** Improved structure and nutrient conditions further enhance microbial diversity and ecological resilience.

This tripartite feedback system transforms recalcitrant organic wastes into "active resources," achieving synergy between waste minimization, soil restoration, and productivity enhancement.

**Conclusions and Future Perspectives**

This research demonstrates that integrating organic waste recycling with targeted microbial symbiosis technologies can fundamentally reshape the fertility trajectory of Albic soil. The combined strategy restores nutrient cycling and structural functionality while establishing a self-sustaining biological network capable of maintaining high productivity with reduced fertilizer input.

The proposed microbe–organic co-amendment model holds profound implications for sustainable agriculture worldwide:(1) It provides a renewable agricultural pathway for organic waste valorization aligned with carbon neutrality goals;(2) It deepens understanding of soil–microbe–organic matter interactions, introducing precise regulation indices centered on enzyme networks, glomalin-related soil protein (GRSP), and co-occurrence networks;(3) It offers theoretical support for region-specific soil restoration technologies with cross-ecosystem applicability.

Future research integrating isotope tracing and transcriptomics will further elucidate microbial carbon flow and key functional gene regulation within this synergistic system. In conclusion, this study provides systematic evidence that when organic residues and beneficial microbes are scientifically coupled, a cyclic, efficient, and resilient soil fertility enhancement pathway can be established. The recovery of Albic soil thus represents not merely nutrient replenishment, but an ecological reconstruction process of rebuilding a living soil matrix.

# Subsoil Mixed Profile Reconstruction Technology

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**ABSTRACT**

According to the World References Base for Soil Resources (WRB), more than ten soil groups are characterized by the presence of an albic horizon or albic materials, which are commonly distinguished by their low organic matter content. In China, Albic soils are widely distributed, with a predominant concentration in Northeast China, particularly in Heilongjiang and Jilin provinces. Among these regions, Heilongjiang Province alone contains approximately 3.31 million hectares of albic soil, accounting for about 10% of the total cultivated land area.Traditionally, the improvement of Albic soils has relied on chemical, physical, biological, and mechanical approaches. However, these methods often suffer from either limited persistence of improvement effects or excessively high implementation costs. In response to the unique soil profile structure of albic soil, a novel soil improvement mechanism has been proposed. This approach maintains the position of the black soil (topsoil) layer while mechanically mixing the two underlying subsoil layers at an appropriate ratio, thereby reconstructing the soil profile. Based on this principle, a specialized soil-improving machine, namely the subsoil mixing machine, has been developed.Mechanical improvement of albic soil through subsoil mixing significantly reduces soil hardness within the albic horizon, alters the vertical distribution of soil moisture, and effectively mitigates surface waterlogging under extreme rainfall conditions by enhancing deep soil water storage capacity. As a result, crop yields increase by approximately 10 –15%, with the improvement effects persisting for 3 –5 years. Furthermore, under subsoil mixing conditions, the additional application of organic amendments markedly increases nutrient availability in the reconstructed albic layer and promotes soil microbial abundance.Overall, subsoil mixed profile reconstruction technology represents a fundamentally effective and sustainable strategy for the improvement of albic soil.

# Ecological Prevention and Control of Early-Stage Gully Erosion in Black Soils: Concepts, Mechanisms, and Integrated Technologies

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**ABSTRACT**

The Northeast China black soil region is one of the most important grain-producing areas in China and a globally significant concentration of high-fertility soils. However, long-term intensive cultivation, inappropriate land-use practices, and the increasing frequency of extreme rainfall events have exacerbated soil erosion, among which gully erosion has become a major driver of black soil degradation and farmland loss. Current management practices tend to prioritize the treatment of large, well-developed gullies, while the far more numerous and widely distributed early-stage gullies receive limited attention. This imbalance has resulted in a typical pattern of "emphasizing treatment over prevention." Statistics indicate that approximately 60% of gully erosion occurs on farmland, and grain losses caused by gully erosion account for nearly one-tenth of the annual marketed grain yield, highlighting the urgency of controlling gully development at its source.

Focusing on the early stage of gully evolution, this study systematically examines key challenges associated with ephemeral gullies, including unclear conceptual definitions, insufficient understanding of development mechanisms, and the lack of predictive and targeted control technologies. Drawing inspiration from the holistic philosophy of traditional Chinese medicine—characterized by "preventing disease before its onset, preventing deterioration after occurrence, and preventing recurrence after recovery"—this study proposes an ecological prevention and control framework for early-stage gully erosion in black soils. By treating hillslopes, flow convergence zones, and gully bottoms as an integrated system, a comprehensive technology package is developed, encompassing potential gully identification, prediction of critical erosion thresholds, optimized configuration of cover crops on slopes, construction of green waterways at gully bottoms, and regulation of gully incision processes.

Results from representative demonstration areas show that cover crops effectively reduce runoff and sediment transport on slopes and contributing areas, while green waterways significantly enhance erosion resistance and suppress gully downcutting by increasing critical hydraulic thresholds. Compared with conventional engineering-based gully treatments, the proposed ecological control system demonstrates clear advantages in terms of cost efficiency, farmland protection, and black soil conservation, with strong potential for large-scale application. This study emphasizes the need to shift black soil management from post-event remediation to process-based prevention, and from localized treatment to systematic governance, providing scientific support and policy-relevant insights for ensuring long-term black soil sustainability, food security, and soil health.

**Acknowledgments**

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# Tillage and straw return alleviate soil compaction in Northeast China: From pore structure to root development and crop productivity

**ABSTRACT**

Soil compaction threatens agricultural productivity by disrupting pore structure and impeding root growth. While tillage and straw management are key mitigation strategies, their synergistic effects on soil aggregate microstructure, compression characteristics, and crop productivity remain incompletely elucidated. A two-year field experiment in Northeast China compared no-tillage with straw return (NTS) and removal (NT), plow tillage with straw return (PTS) and removal (PT), and subsoiling tillage with straw return (STS) and removal (ST). Synchrotron-based X-ray micro-computed tomography quantified aggregate pore characteristics, and uniaxial confined compression tests assessed soil compression properties, alongside root traits and yield measurements. Results showed that plow tillage and subsoiling tillage reduced bulk density and penetration resistance compared to no-tillage. STS enhanced subsoil organic carbon (30.7–124.9%). These two tillage practices increased aggregate total porosity (68.7–153.4%) and connectivity porosity (84.1–204.5%), and enhanced the proportions of macropores (75–100 μm) and megapores (>100 μm). Straw return to the subsoil further amplified these pore improvements. Plow tillage and subsoiling tillage decreased pre-compression stress ($\sigma_p$) while increasing compressibility (Cc) and recovery coefficient (Rc), benefits significantly enhanced by straw return under STS. These practices also increased root length, surface area, and volume while decreasing average diameter, resulting in STS achieving the highest maize yield (10.1 Mg ha$^{-1}$) in the second year. Partial least squares path model revealed tillage practice negatively affected $\sigma_p$ and positively affected Rc, while porosity positively influenced Cc. Redundancy analysis confirmed strong links between soil parameters and plant parameters. Overall, subsoiling tillage with straw return (STS) alleviated soil compaction through optimizing pore structure, organic carbon, and compression characteristics, promoted root development, and thereby enhanced yield. This practice provides a scientifically feasible strategy for sustainable agricultural development in Northeast China.

**Keywords:** Soil compaction, SR-μCT, Aggregate pore structure, Deep straw incorporation, Subsoiling tillage

# Bacterial richness enhances the thermostability of soil organic matter: long-term perspective

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**ABSTRACT**

The persistence of soil organic matter (SOM) is influenced by its molecular features and stable status. However, the temporal dynamics of these features remain unclear. Here, we employed FT-ICR mass spectrometry to investigate the molecular diversity (number of molecules) and molecular thermodynamic-stability (the theoretically Gibbs free energy for the half reaction of carbon oxidation) of SOM in soils from long-term (> 30 years) paddy and upland experimental fields. Thermogravimetric analysis showed that enhanced SOM thermostability (the thermal decomposition resistance of total SOM) aligns with the temporal variation of molecular thermodynamic-stability in these soils. We observed that increased SOM molecular thermodynamic-stability occurs alongside decreased molecular diversity over decades, and this temporal trade-off (negative relationship) is modulated by increased bacterial richness. Microbial communities with richness gradients were established using a dilution-to-extinction approach and were further inoculated into a sterilized soil for 90 days, and the subsequent measurements of SOM molecular diversity and thermodynamic-stability reproduced the aforementioned temporal trade-off relationship. Overall, our findings demonstrate that higher bacterial richness facilitates the selective transformation of SOM into a chemically more stable molecular pool and enhances SOM thermostability over decades, suggesting that agronomic fertilization strategies promoting bacterial richness are more likely to contribute to improved SOM persistence in agricultural food systems.

**Acknowledgments**

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# Carbonic Anhydrase Enabled Synergies for Enhanced Microalgal $CO_2$ Fixation: From Enzyme Production to Engineered Microbial Consortia

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**ABSTRACT**

Microalgae are promising platforms for biological carbon capture and utilization/storage (CCU/CCS), yet their large-scale deployment is constrained by inefficient $CO_2$ hydration and mass transfer, resulting in limited $CO_2$ delivery to the RuBisCO carboxylation site under industrial flue-gas conditions. In an internal-LED flexible air-lift photobioreactor operated at 20% $CO_2$, exogenous carbonate anhydrase (CA) markedly enhanced carbon-concentrating mechanisms in Chlorella sp., leading to increased chlorophyll, lipid, and protein accumulation, elevated key carbon-flux intermediates such as malate and succinate, enhanced RuBisCO and acetyl-CoA activities, reduced oxidative stress, and strengthened extracellular electron transfer. To enable scalable and cost-effective deployment, Mesorhizobium loti carbonic anhydrase (MlCA) was produced via high-throughput promoter screening in Escherichia coli, achieving a specific activity of 34.6 WAU $mg^{-1}$ and rapidly catalyzing $CO_2$ mineralization to calcite ($CaCO_3$) under mild conditions, supporting integrated CCU/CCS strategies. Transitioning from enzyme supplementation to autonomous systems, mutualistic *Chlorella* sp.–M. loti co-cultures stabilized pH, coupled carbon and nitrogen metabolism, and increased total $CO_2$ fixation by 34.1% at 20% $CO_2$, with nitrogen transfer reaching 18% on day 2 as quantified by $^{15}N$ isotope labeling. Further enhancement was achieved using a facultative autotroph, Cytobacillus KQ-2, which genomically encodes both Calvin-Benson-Bassham and reductive TCA carbon fixation pathways and formed a highly synergistic consortium with *Chlorella*, increasing total $CO_2$ fixation by 52.11% over 10 days at 20% $CO_2$; metabolomic and electrochemical analyses revealed intensified metabolic cross-feeding, reinforced antioxidant networks, reduced reactive oxygen species, and enhanced interspecies electron transfer. Collectively, CA-enabled microalgal systems spanning low-cost enzyme production, reactor-level intensification, and engineered microbial consortia provide a mechanistically grounded and scalable pathway for high-$CO_2$ flue-gas treatment and next-generation biological CCU/CCS.

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# Monitoring Ecological Rehabilitation of Degraded Soils by Human Activities Using Thermal Indicators of Soil Organic Matter

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**ABSTRACT**

Degradation of soil functions by human activities in urban areas poses significant challenges to ecological health and urban sustainability. Effective rehabilitation of these soils requires reliable indicators that reflect changes in soil quality and functioning over time. This study explores the use of thermal indicators of soil organic matter (SOM), derived from thermal Rock-Eval® analyses (a pyrolysis and oxidation-based method), as a promising tool for monitoring ecological rehabilitation actions in anthropized soils. By assessing the thermal carbon stability and content of SOM, Rock-Eval® indicators offer insight into the SOM quality and properties (labile and recalcitrant forms of soil carbons) after rehabilitation actions and allow monitoring of soil re-functionalization. In this work, a gradient of rehabilitation effort was designed and implemented in an urban site in France (Pierre-Bénite) to evaluate the influence of varying soil amendments, treatments, and plantations on soil function recovery (e.g., soil decompaction, bio-techno materials, etc.). Thermal indicators of SOM were estimated at three different stages: the initial phase of rehabilitation, short-term (2.5 years), and long-term (7.5 to 8.5 years).

Regarding the thermal properties of SOM (hydrogenation, oxygenation, lability, and stability of organic matter), the most significant rehabilitation effort (techno-soil with high organic matter amendment) is largely dominated by HI/OI values. Intermediate rehabilitation efforts (techno-soils with low organic matter amendment) show a typical signature of subsoils. In contrast, the low-cost rehabilitation effort (no organic matter amendment) is also characterized by a SOM of subsoils, which evolves rather towards a typical signature of topsoils over time. After 8.5 years, a clear difference between the techno-soils is observed, linked to the decomposition of the more labile components (I-index) and an increase in the thermal stability of the SOM (R-index). The low-cost rehabilitation effort modality is dominated by a more stable organic matter over time. A relative increase in soil organic carbon (SOC) content over time is also observed for all modalities, especially for the most significant rehabilitation effort, which is dominated by much higher SOC values.

Finally, results from field and laboratory assessments demonstrate a correlation between the progression of soil rehabilitation and shifts in SOM thermal properties, indicating substantially enhanced agricultural and forestry productivities of SOM. Nevertheless, the magnitude of this improvement seems to be inversely proportional to the intensity of rehabilitation effort, suggesting that low-cost actions can be competitive in the long term. This research highlights the potential of thermal carbon stability indicators (e.g., I, R indices, SOC, HI/OI) as cost-effective, sensitive, and integrative tools for assessing soil health and guiding urban ecological restoration strategies.

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# Developing a diffusive gradients in thin films (DGT) technique for large-scale and high-resolution mapping of labile potassium in soils

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**ABSTRACT**

Potassium (K) is essential for plant growth, yet only a small fraction in soil is available to plants. Traditional extraction methods, such as ammonium acetate ($NH_4OAc$), provide measurements of exchangeable K but overlook its diffusion and spatial dynamics. This study developed and validated a diffusive gradients in thin films (DGT) technique using a cation exchange membrane (CXM-200) to assess K availability and movement, using polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$) fertiliser in soil. The CXM-DGT had a good detection limit (9.93 µg/device), high binding capacity (1687 µg at 0.01 M ionic strength), and stable performance across pH 3.5–8.5 and ionic strengths up to 0.01 M $NaNO_3$. Its results were comparable to Amberlite IRP-69 DGT for K measurement but with advantages of easier use and reusability. The presence of competing cations ($Ca^{2+}$, $Mg^{2+}$) slightly affected performance, and shorter deployment times (~6 h) were recommended to minimise interference in cation-rich soils. Coupling CXM-DGT with X-ray fluorescence microscopy (XFM) enabled high-resolution mapping of K distribution. After incubation for one week, Alfisol soils exhibited peak available K concentrations (49.6 ± 16.8 mg/L) at the fertiliser band, decreasing beyond 20 mm. In contrast, the clay-rich Oxlsol showed lower K concentrations (21.4 ± 15.4 mg/L). Lateral K distribution patterns from CXM-DGT closely matched exchangeable K measured via $NH_4OAc$ extraction, both showing steep declines away from the fertiliser zone. The stronger K binding in the Oxlsol highlights the role of clay content and mineral surfaces in controlling K mobility and availability. Overall, the CXM-DGT technique provides a robust and high-resolution method for quantifying K diffusion and spatial lability in soils. When integrated with XFM, nutrient gradients around fertiliser bands can be visualised. These results highlight how soil texture and mineralogy regulate K redistribution. The combined CXM-DGT and XFM approach can be used to provide valuable insights into developing more efficient and sustainable K fertilisation practices.

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# Single-cell exploration of the microbiota driving soil phosphorus mobilization: from single-cell Raman to high-throughput fluorescence profiling

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**ABSTRACT**

Phosphorus (P) limitation in agriculture demands efficient mobilization of soil-fixed P. While phosphate-solubilizing bacteria (PSB) offer a sustainable solution, current methods struggle to isolate truly functional strains[1]. We developed a hierarchical single-cell approach to directly target in situ active PSB[2]. Initially, single-cell Raman spectroscopy with $D_2O$ probed PSB activity under fixed-P conditions, but its low throughput (1-60 cells/min) limited comprehensive analysis. To address these challenges, our research introduces an innovative single-cell analysis framework, designed to progress from direct targeting to high-throughput functional mining of the active community. We developed a high-throughput method that uses fluorescent D-amino acid (FDAA) labeling under fixed-P stress to sort metabolically active PSB through fluorescence-activated cell sorting, enabling direct downstream applications of sorted cells for cultivation and sequencing. This strategy revealed unprecedented diversity, identifying 11 previously unreported genera and substantial unclassified taxa. Targeted cultivation yielded 71 isolates across 19 genera, with six genera and 11 potential new species first reported as PSB. Notably, 61% of isolates originated from rare (<0.1% abundance) taxa. Soil validation showed key isolates released fourfold more bioavailable P and maintained colonization for over three weeks, outperforming commercial strains. This function-driven platform directly links microbial identity to in situ activity and cultivability, providing a scalable strategy for mining hidden microbial resources to advance sustainable agriculture.

**Keywords:** Single-Cell Analysis, Phosphate-Solubilizing Bacteria (PSB), Raman-$D_2O$, Fluorescent D-Amino Acids (FDAA), Sustainable Agriculture

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# The Soil iMAPS Initiative: a global network to map the single-cell in-situ metabolic atlas for soil

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## ABSTRACT

The soil microbiome regulates vital soil functions, including nutrient cycling, soil structure formation, and the suppression of plant diseases. However, metabolic monitoring and mining for in-situ functional microbes have been challenging, due to the inability to rapidly untangle the single-cell "6W" questions: What metabolic functions are being performed (doing What), Who it is (Who), Why they perform these functions (Why), generating Wealth (pure cultures), When, and Where. To systematically investigate these questions and elucidate their spatiotemporal patterns at both local and global scale, we developed the Metaramanomics Platform, which consists of FlowRACS, RAMS, and DCP (Digital Clone Picker). The platform enables label-free, rapid, high-throughput, low-cost profiling, sorting and cultivation of soil microbiota based on in situ metabolic phenome in a “screen first, culture second” fashion. Based on this platform, over 20 institutions worldwide jointly launched the Soil iMAPS (https://www.iMAPS.info), to establish a global network of facilities for metabolic sensing, strain mining, and ecological restoration of soil microbiomes. This will accelerate the translation of soil microbiota into deployable solutions for tackling global warming, food security, water shortage and degradation of farmlands. This presentation will report the latest progress from the Soil iMAPS Initiative.

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https://www.imaps.info/Solutions

# Loosely bound mobile metal ions distribution across arid landscapes

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**ABSTRACT**

Heavy metals in soils represent a major category of pollutants, regardless of their origin—be it from anthropogenic activities or the natural leaching of bedrock. The hypothesis of a natural source for elevated metal concentrations opens avenues for soil research that extend beyond pollution assessment and agriculture, positioning it as a tool for geochemical prospecting. A critical challenge is identifying specific metal forms, for which sequential extraction techniques provide valuable differentiation and insight into metal mobility and origin.

This study applied a ligand-based extraction method targeting mobile metal fractions, underpinning the ATHAR-M hydrocarbon prospecting technique. This approach detects trace inorganic markers mobilized from depth via hydrocarbon microseepage, generating geochemical anomalies in surface soils. Mobile, weakly bound heavy metals serve as primary indicators.

We analyzed 345 soil samples from eight arid-region fields dominated by aridisoils. Mobile metal ions were extracted using a ligand solution selective for weakly bound ionic forms and quantified by high-precision ICP-OES. Optimal extraction conditions and key indicator elements (V, Ni, Cu, As, Ti) were established.

Results revealed significant spatial variability in metal concentrations. Vanadium concentrations exceeded 30 ppm with multiple outliers above 5 ppm, contrasting with median background levels below 2 ppm. Five fields exhibited right-skewed vanadium distributions; one field showed a standard deviation of 4.7 ppm (n=45). Nickel displayed similar heterogeneity, with maximum concentrations above 1 ppm and baselines near 0.15 ppm. Other elements followed comparable distribution patterns, varying by field.

These pronounced inter-field differences suggest metal enrichment arises from both bedrock weathering and natural hydrocarbon microseepage. Our findings demonstrate that combining selective chemical extraction with ICP-OES provides a sensitive and precise method for detecting subtle geochemical anomalies relevant to hydrocarbon prospecting.

# Raman-based flow cytometry for single-cell microbial phenotyping

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**ABSTRACT**

Raman microspectroscopy offers a direct and efficient approach to identify and classify target microorganisms based on their phenotypic characteristics (e.g., metabolic activities and functional roles) within complex microbial communities. In this talk, I will demonstrate how this technology can be integrated with a fluidic system to enable automated, high-throughput Raman-based flow cytometry. The platform incorporates five core enabling technologies: Raman microspectroscopy, microfluidics, optical tweezers, stable isotope probing (SIP), and software automation. A model bacterial strain, *Escherichia coli*, was used for platform development and validation, after which the system was applied to a natural complex sample — the mouse colon microbiome. Using this approach, mucin-degrading bacteria were selectively sorted, and downstream metagenomic analysis confirmed that function-driven Raman flow cytometry directly links target cell phenotypes to their genotypes. Furthermore, artificial intelligence was integrated into the platform as an adaptive sorting criterion for nitrite-oxidizing bacteria in marine sediment samples, in which Raman signatures varied depending on physiological states. Collectively, Raman-based flow cytometry establishes a powerful new avenue for intuitively bridging microbial phenotypes and genotypes at the single-cell level.

**Acknowledgments**

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# Evaluation of ion selective electrodes for monitoring plant nutrients

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**ABSTRACT**

Global population is projected to increase to about 10 billion by 2050, with a corresponding 100% increase in global food demand. Meanwhile, sustainable farming – which requires an annual use of fertilizers and agrochemicals to the tune of 200 million metric tons – is central to meeting this demand. Consequent upon this, is the detrimental effects on soil health, human health, aquatic lives and food chain, following an uncontrolled use of these resources. The aim of this research is the first split evaluation of plant available nutrients in soil treated with novel fertilizers combination (AN – ammonium nitrate; OMP – organo-mineral pellets and FYM – farmyard manure) in three splits. Ion selective electrodes (ISEs) have been identified as a suitable technology - due to their simplicity, affordability and portability – to achieving this. Presented herein, are characterization of key response characteristics of ISEs (slope, limit of detection, signal stability) to determine nitrate and ammonium ions (two key nitrogen-containing species uptake by plants) in a range of soil samples obtained from School of Agri-Food Technology and Manufacturing, Riseholm Campus, University of Lincoln, Lincoln, U.K. Eight soil samples were analysed in quadruplicates and results validated with Ion Chromatography. Membranes calibration was done, under uncontrolled general laboratory temperature, using various volumes of ammonium nitrate solution in concentrations ranging between 1 M and $10^{-3}$ M. Calibration results obtained showed that the slope, limit of detection and membranes responses obeyed the principles of both Nernstian and Nikolskii-Eisenman theory within the range tested (NH4+: y = 58.972x + 709.29, R^2 = 0.9946; NO3-: -55.705x + 255.79, R^2 = 0.9324). Meanwhile, ISEs recorded higher nitrate concentrations in 100% of the sample plots than I.C, with concentrations ranging from 47.01 mg/Kg to 14.38 mg/Kg and 4.97 mg/Kg to 3.77 mg/Kg respectively. Although, the concentration of nitrate in the fertilizers added per Kg of soil in the first split was low, however, this concentration is closer to ISEs analysis results but far higher than the I.C results. Similarly, ammonium analysis by ISEs recoded higher concentrations in 100% of the sample plots than analysis by I.C, with concentrations ranging from 13.79 mg/Kg to 5.58 mg/Kg and 5.97 mg/Kg to 1.79 mg/Kg respectively. There are disparities between the two methods, which can be attributed to the high sensitivity of ISEs in responding to low nutrient concentration in soil, rather than systemic bias from matrix effect or background interferences. In conclusion, although this is a first year Ph.D. research, however, polymer membrane-based ISE technology has shown promising potentials as an analytical method of choice for the evaluation of soil "available" nutrients, using the right amounts of selective ionophores.

# Designing drought-resilient plant microbiomes using single-cell Raman spectroscopy

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## ABSTRACT

Plant-associated microbiomes are increasingly recognized as key determinants of crop performance under environmental stress, particularly drought. However, a fundamental limitation in plant microbiome research is the inability to directly link microbial identity with *in situ* metabolic activity and stress tolerance. Sequencing-based approaches infer functional potential from gene content but cannot resolve phenotypic heterogeneity, dormancy, or activity differences among closely related taxa. Single-cell Raman microspectroscopy provides a label-free, non-destructive technique that captures biochemical fingerprints of individual microbial cells based on molecular vibrations of proteins, lipids, nucleic acids, and carbohydrates. When combined with stable isotope probing, particularly heavy-water ($D_2O$) labeling, Raman spectroscopy enables direct quantification of microbial metabolic activity through the formation of C–D bonds in newly synthesized biomass, offering a universal, substrate-independent measure of cellular activity. Recent advances in Raman-activated cell sorting further allow the targeted isolation and downstream genomic characterization of functional microbial populations, establishing Raman spectroscopy as a powerful "next-generation physiology" tool for resolving plant–microbe interactions at single-cell resolution.

Applying $D_2O$-labelled single-cell Raman spectroscopy to the wheat rhizosphere under graded drought stress, we observed a significant enrichment of metabolically active drought-tolerant bacteria (DTB) as drought severity increased. Raman C–D ratio distributions revealed strong functional skewness, with a small fraction of highly active cells contributing disproportionately to community-level metabolic activity. Targeted Raman-based sorting and sequencing identified 21 active DTB taxa enriched in genes related to osmotic stress regulation, phytohormone synthesis, biofilm formation, and carbon, nitrogen, phosphorus, and sulfur cycling. DTB activity was tightly coupled to drought-induced plant phytochemicals, including jasmonic acid, pipecolic acid, phenylpropanoids, and gibberellins, indicating metabolite-driven microbial selection. Importantly, a synthetic community constructed from four Raman-identified DTB strains significantly improved wheat growth and drought resistance, directly linking Raman-defined microbial phenotypes to plant fitness outcomes.

Our work demonstrates that single-cell Raman spectroscopy overcomes key limitations of traditional microbiome analyses by directly resolving microbial activity, stress tolerance, and ecological function within plant-associated communities. Integrating Raman-based phenotyping with microbiome ecology provides a robust framework for identifying functionally important microbes and enables trait-informed strategies for microbiome-assisted crop resilience in a changing climate.

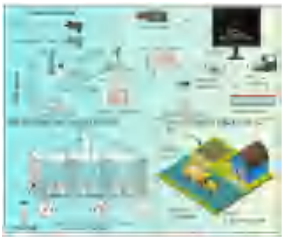


**Figure 1** Functional single-cell Raman–SIP framework for designing beneficial SynComs to enhance plant resilience

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# Micro-CT scanning as a tool for analysing comparative root architecture of pasture species

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**ABSTRACT**

Understanding root architecture is essential for improving pasture persistence and productivity under changing climates; however, measuring roots directly is challenging and often requires root washing that disturbs the spatial distribution of roots. We used X-ray micro-computed tomography (micro-CT) scanning as a non-destructive imaging technique to characterise and quantify root architecture of pasture plants within a controlled soil column (25 cm height, 65 mm inner diameter) system.

Three pasture species, a grass (*Lolium perenne* cv. Base AR37), a legume (*Trifolium repens* cv. Legacy) and a herb (*Cichorium intybus* cv. Puna II), were grown individually from seeds in a sand medium and were scanned multiple times using micro-CT. High-resolution (65 micrometre voxels) 3D image data sets were collected, segmented and processed to identify the presence and distribution of roots along the vertical axis at 3 cm intervals of the soil column.

Micro-CT scanning successfully detected root systems in all soil columns, which revealed inter-species differences in root distributions. At the surface (0-3 cm), the herb had the greatest presence of roots (0.54 $cm^3$), followed by grass (0.32 $cm^3$), and then the legume (0.11 $cm^3$). At greater depths (6-9 cm), the herb and grass were similar and had greater root volume than the legume. Near the bottom of the soil column (> 15cm), the herb had greater root volume than both the grass and legume, indicating a deeper and more extensive root system. These findings highlighted the potential of micro-CT to decipher species-specific rooting strategies in a pasture system with acquired three-dimensional datasets.

This study demonstrated the value of the X-ray micro-CT scans as an advanced instrumental technique for non-destructive root phenotyping and quantitative analysis without affecting the growth of the scanned species. This approach provides a robust methodological framework for future studies that plan on repeatedly investigating root architecture in pasture species.

**Acknowledgments**

We acknowledge the Melbourne Trace Analysis for Chemical, Earth and Environmental Sciences (TrACEES) Platform for providing access to the micro-CT scanner.

# Evolutionary engineering of microbial communities to combat aluminum toxicity in acidic soils

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**ABSTRACT**

Aluminum (Al) toxicity in acidic soils poses a major constraint to both plant productivity and microbial functionality, yet the adaptive evolution and practical applications of plant growth–promoting rhizobacteria (PGPR) under chronic Al stress remain poorly understood. Here, we combined experimental evolution, single-cell Raman–D2O spectroscopy, and multi-omics analyses to dissect the Al tolerance of three PGPR strains and their associated plant benefits. Over a 32-day evolution, as observed in single-cell metabolic activity, Al-tolerant subpopulations progressively became dominant with the proportion of tolerant cells increasing to 58.9–96.2%. Whole-genome and transcriptomic analyses revealed coordinated mutations and lineage-specific transcriptional reprogramming that remodel metabolism, strengthen cellular structures, and activate distinct stress-response functions to confer Al tolerance across evolved strains. Additionally, the evolved isolates and their synthetic communities (SynComs) increased rhizosphere pH, reduced Al bioavailability, and enhanced rice growth under both hydroponic and soil conditions. Notably, SynCom inoculation reduced shoot Al content by up to 58.9% in acidic soil. Furthermore, the rhizobacterial community was enriched with beneficial plant-associated taxa following SynCom inoculation. Together, these findings establish a scalable framework for evolving and assembling Al-tolerant PGPR to mitigate Al toxicity and enhance crop resilience in acid soils.

**Acknowledgments**

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# Discrimination and Quantification of Soil Nanoparticles by Dual-Analyte Single Particle ICP–QMS

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**ABSTRACT**

This study presents the new application of dual-analyte single particle inductively coupled plasma quadrupole mass spectrometry (spICP–QMS) to the discrimination and quantification of two typical soil nanoparticles (kaolinite and goethite nanoparticles, abbr. KNPs and GNPs) in three samples (SA, SB, and SC) with three detection events (Al unpaired event, Fe unpaired event, and paired event). SA was mainly composed of KNPs with a concentration of 28443 ± 817 particle $mL^{-1}$ and a mean particle size of 140.7 ± 0.2 nm. SB was mainly composed of GNPs with a concentration of 39283 ± 702 particle $mL^{-1}$ and a mean particle size of 141.8 ± 2.9. In SC, the concentrations of KNPs and GNPs were 224541 ± 1401 and 70604 ± 1623 particle $mL^{-1}$, respectively, and the mean particle sizes of KNPs and GNPs were 140.7 ± 0.2 and 60.2 ± 0.3 nm, respectively. The accuracy of dual-analyte spICP–QMS was determined by spiking experiments, comparing these results with the measurements of other techniques, analyzing the samples in different SA and SB proportions and in different SC concentrations. Our results demonstrated that the dual-analyte spICP–QMS is a promising approach to distinguishing different kinds of natural NPs in soils.

**Acknowledgments**

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# Quinolone-mediated metabolic cross-feeding develops aluminium tolerance in soil microbial consortia

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**ABSTRACT**

Aluminium (Al)-tolerant beneficial bacteria confer resistance to Al toxicity to crops in widely distributed acidic soils. However, the mechanism by which microbial consortia maintain Al tolerance under acid and Al toxicity stress remains unknown. Here, we demonstrate that a soil bacterial consortium composed of *Rhodococcus erythropolis* and *Pseudomonas aeruginosa* exhibit greater Al tolerance than either bacterium alone. P. aeruginosa releases the quorum sensing molecule 2-heptyl-1H-quinolin-4-one (HHQ), which is efficiently degraded by *R. erythropolis*. This degradation reduces population density limitations and further enhances the metabolic activity of *P. aeruginosa* under Al stress. Moreover, *R. erythropolis* converts HHQ into tryptophan, promoting the synthesis of peptidoglycan, a key component for cell wall stability, thereby improving the Al tolerance of *R. erythropolis*. This study reveals ametabolic cross-feeding mechanism that maintains microbial Al tolerance, offering insights for designing synthetic microbial consortia to sustain food security and sustainable agriculture in acidic soil regions.

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# From lab to field: An open-source, low-cost toolkit for soil $CO_2$ respiration research

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**ABSTRACT**

Soil $CO_2$ respiration is a fundamental component of the terrestrial carbon cycle and a key determinant of ecosystem carbon budgets and climate feedbacks. Accurate quantification of soil–atmosphere $CO_2$ exchange requires measurements that resolve temporal and spatial variability, whereas interpretation of subsurface dynamics and carbon source attribution requires depth-resolved monitoring complemented by incubation experiments. However, existing commercial approaches—such as flux chambers, eddy-covariance towers, and instrumentation for soil profile monitoring and laboratory incubations—are often costly, labor-intensive, and logistically demanding, limiting their applicability for long-term, high-replication studies, particularly in remote or resource-limited environments. Here, we present a toolkit of three complementary, low-cost, open-source systems that together enable surface flux measurements, depth-profile monitoring of subsurface processes, and laboratory incubations for mechanistic soil respiration research. The first component is a portable incubation chamber system designed to support controlled, replicated laboratory soil respiration experiments (Nguyen et al., 2025a). The second component is a gradient-based sensor system that enables subsurface monitoring of soil $CO_2$, temperature, and relative humidity, together with atmospheric microclimate measurements (temperature, pressure, and relative humidity) (Nguyen et al., 2025b). A complete processing workflow is provided to derive soil $CO_2$ fluxes from depth-resolved concentration profiles using Fickian diffusion, and the system has demonstrated strong agreement with LI-COR References chambers. The third component is an automated flux chamber based on a closed dynamic approach, which has been tested under in situ conditions and shows good agreement with both LI-COR and Eosense systems across a wide range of fluxes. All three systems are fully open source, with openly available hardware designs, source code, and technical documentation, enabling users with limited prior experience to build, deploy, and adapt the systems for their own soil respiration studies.

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# Nitrogen-fixing seed endophytes synergize with soil functional microbiota to enhance rice nitrogen supply

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**ABSTRACT**

Rice (*Oryza sativa* L.) relies heavily on substantial nitrogen (N) inputs to ensure yield. Notably, *indica* rice subspecies generally exhibit higher N-use efficiency (NUE) compared to *japonica* subspecies. Plant microbiomes significantly influence rice N supply. Seed endophytes constitute a major source of the core plant microbiomes, particularly those functional ones, such as N-fixing microorganisms. However, the role and mechanism of functional seed endophytes in modulating rice N supply remain to be elucidated. Here, we investigated the N-fixing capacity of seed endophytes from multiple *indica* and *japonica* varieties. Results showed a significantly higher abundance of N-fixing genes in *indica* seeds than those in *japonica* seeds. Concurrently, distinct differences were observed in the N-fixing bacterial communities, with *indica* seeds enriched in bacteria such as *Paenibacillus* and *Bradyrhizobium*. Integrating high-throughput sequencing with pure-culture techniques, we selected the most abundant *Paenibacillus* from *indica* for in-depth study. *Paenibacillus* sp. JS-27, isolated from the conventional *indica* male parent 93-11, was ultimately chosen. Inoculating the *japonica* variety "Nangeng5055" with JS-27 significantly enhanced plant biomass and total N accumulation compared to non-inoculated plants. Further, scanning electron microscopy of inoculated seeds showed that JS-27 colonized the seed surface early and migrated to the roots of emerging seedlings upon germination, with some cells dispersing into the rhizosphere soil. To investigate whether JS-27, after soil migration, could also influence rice N supply by modulating the soil microbiome, we conducted inoculations under both natural and sterile soil conditions. The promotion of N uptake and plant growth by JS-27 was more pronounced in natural soil. Moreover, soils from the inoculated group showed significant enrichment of ammonia-oxidizing bacteria. Application of the nitrification inhibitors allylthiourea (ATU) and nitrapyrin (NRP) showed that JS-27-promoted rice growth was compromised by both inhibitors, concomitant with the reduced expression of *amoA*, and diminished JS-27-drived increase of rhizosphere nitrate/ammonium ratio. Experiments using an NRT1.1B knockout mutant (*nrt1.1b*, Zhonghua 11 (ZH11) background), which impairs nitrate transport, showed that in natural soil, the growth-promoting effect of JS-27 on *nrt1.1b* was significantly decreased compared to wild-type ZH11. Additionally, analysis of rhizosphere soils from multiple *indica* and *japonica* varieties across major rice-growing provinces in China revealed a potential correlation between the abundances of N-fixing and ammonia-oxidizing bacteria. These results demonstrate that *Paenibacillus* sp. JS-27 drives soil ammonia oxidation, which cooperatively enhances rice N supply and growth. To enhance stable colonization and efficacy, we embedded *Paenibacillus* sp. JS-27 onto seed surfaces using sodium alginate and pectin. This microbial seed coating treatment significantly increased total N content and yield compared to non-inoculated treatments. The present work provides insight into how the seed N-fixing microbes promote rice N supply and offers a promising strategy for optimizing crop growth by harnessing the functional seed microbiota for sustainable agriculture.

**Keywords:** Rice, N supply, Seed microbiome, N-fixing bacteria, Ammonia-oxidizing microbes

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# In situ Non-destructive Imaging of Roots from GFP-Expressing Plants Using a Novel Fluorescence Minirhizotron with Automated Intensity Measurement and CNN-based TRL Estimation

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**ABSTRACT**

*In situ* and non-destructive root phenotyping remains a challenge due to the difficulty of continuous monitoring, of recognizing roots within a complex soil matrix and generating a robust, automated analysis workflow. Here, we present a novel fluorescence minirhizotron (FMR) system that simultaneously obtains root images of green fluorescent protein (GFP) fluorescence and regular visible-light root images, taken at the same time and position, allowing for a direct comparison between the two. The root fluorescence images originate from a constitutively GFP-expressing transgenic 16c line of *Nicotiana benthamiana* with wild-type serving as the non-GFP fluorescent control. A pilot system was initially tested based on root imaging with rhizoslides and, later, in a real-world scenario using the FMR system in soil, thereby demonstrating the system's robustness and applicability across a wide range of scenarios. A total of 1,080 and 2,108 images with the pilot system and the FMR, respectively, were collected, each comprising equal numbers of visible-light and corresponding GFP images. From these images, 100 pilot-system and 204 FMR images were manually annotated for total root length (TRL) using Rootfly software. In addition, we present an automated solution for GFP intensity measurements, comparing four thresholding methods. We also incorporate automated TRL analysis for imaging types, using a well-established convolutional neural network model which achieves $R^2$ values of 0.93-0.99 for the automatic TRL estimations. These automated methods were used to successfully differentiate between GFP-expressing and non-expressing plants, which cannot be achieved based on regular bright-field imagery.

**Keywords:** Root, minirhizotron (MR), green fluorescence protein (GFP), total root length (TRL), Convolutional neural networks (CNNs).

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# Green Surfactant Remediation of Petroleum Hydrocarbon-Contaminated Soil and Bacterial Community Response

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**ABSTRACT**

Soil contamination by total petroleum hydrocarbons (TPH) has become a prominent global environmental issue, which severely threatens soil ecosystem functions, groundwater security and human health. Surfactant-enhanced soil washing is widely applied in TPH-contaminated soil remediation, yet the ecological impacts of green surfactants on soil bacterial communities, especially the dynamic changes of microbial co-occurrence networks and the succession of keystone taxa during washing and post-remediation recovery, remain largely unclear. In this study, a laboratory column experiment was conducted using rhamnolipid and rhamnolipid-alkyl polyglucoside (APG) green surfactant systems at low and high concentrations, with four sampling stages including original control (CB), post-washing (L), 30-day incubation (T30) and 60-day incubation (T60). We systematically analyzed TPH removal efficiency, soil physicochemical properties, bacterial community structure, co-occurrence network topological characteristics and multi-method identified keystone taxa. The results of non-metric multidimensional scaling (NMDS) showed that sampling stage rather than surfactant type and concentration was the dominant driving factor of bacterial community structural divergence. The co-occurrence network analysis revealed that surfactant washing significantly enhanced microbial interspecies connectivity but reduced community stability, and the network structure gradually recovered to the native state with the extension of incubation time. Keystone taxa analysis indicated that the abundance of core functional taxa decreased sharply after washing and recovered rapidly during recovery, which was highly coupled with network stability and TPH degradation efficiency. Among all treatments, the low-concentration rhamnolipid-APG mixture (M1) achieved the highest TPH removal efficiency (77.2% at 60 days), with mild disturbance to soil bacterial communities and rapid recovery of network structure and keystone taxa. This study confirms that the low-concentration rhamnolipid-APG mixture is an optimal green surfactant system for TPH-contaminated soil remediation, and provides important theoretical support and technical References for efficient and eco-friendly in-situ remediation of TPH-contaminated sites with built infrastructure.

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# Contrasting soil functional responses to climate change in restored and spontaneously colonized mine tailings

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**ABSTRACT**

Metalliferous mine tailings pose major environmental hazards and hinder biotic colonization due to their harsh conditions (high levels of metals/metalloids and salts, scarcity of organic matter and nutrients). Traditional restoration based on topsoil capping and revegetation is costly and can yield ecosystems with limited long-term sustainability, especially in semiarid regions. As a nature-based alternative, phytomanagement, particularly phytostabilization, relies on the ability of certain plants to establish directly on mine wastes, reducing pollutant mobility and enhancing soil functions. This approach can be strengthened by studying native vegetation that spontaneously colonizes tailings and underlying soils, offering a natural model of passive restoration. Because restoration seeks to minimize human and environmental risks over the long-term, understanding how tailing soils respond to climate change is essential.

This study experimentally evaluated the effects of climate change on the functionality of soils from mine tailings differing in their management history over the last 40 years: one technically restored through topsoil capping and pine afforestation, and another spontaneously colonized by native vegetation. Soils were collected from both type of tailings in the La Unión-Sierra de Cartagena mining district (SE Spain, semiarid region), one of Europe's major 20th-century mining areas, which currently hosts 89 tailings, most of them unrestored. Soils were sampled under two types of vegetation cover (shrubs and pines) and incubated for four months in climate-controlled chambers (two months simulating spring and two summer) under three IPCC-based scenarios: current climate (450 ppm $CO_2$, current temperature), moderate warming (700 ppm $CO_2$, +3 °C), and strong warming (1000 ppm $CO_2$, +5 °C). A range of soil physicochemical and biological indicators were analyzed, including enzyme activities (C, N, P cycles), microbial biomass C and N, microbial community composition, and C and N mineralization.

Results showed that soil responses varied across climate scenarios and were modulated by both tailing management history and type of vegetation cover. Microbial biomass and enzyme activities were particularly sensitive to climatic stress, with stronger shifts in restored tailing soils. Spontaneously colonized tailing soils displayed more stable patterns, suggesting higher resilience to climate change. Across both tailings, bacterial richness decreased under moderate and strong warming, whereas functional diversity increased in colonized soils, indicating potential microbial adaptation. These findings highlight the need to integrate climate change projections into mine tailings management, promoting nature-based restoration strategies that enhance soil resilience and long-term ecosystem stability in semiarid environments.

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# Geochemical Fractions of Pb and Ni in Orchard Soils and Ecological Risk Assessment Using Pollution Indices

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**ABSTRACT**

While inputs from natural sources constitute a significant burden of trace elements, for most elements the contribution from anthropogenic sources is much greater than from natural sources, raising environmental and health concerns [1]. Heavy metals from anthropogenic sources also tend to be more mobile and therefore more bioavailable compared to pedogenic or lithogenic sources [2]. The contribution of anthropogenic sources can be more reliably determined by the amount of heavy metals in the non-residual fraction rather than their total amount. In surface soils (0-10 cm), the contribution of anthropogenic sources to Cu, Zn, Pb and Ni in the non-residual fraction, i.e. the readily and potentially bioavailable and mobile fraction, was 51%, 70%, 24% and 49%, respectively [3].

Contamination of soils and arable land with trace elements such as Cu, Zn and Pb can occur due to the transfer of these elements into the fertilizer during the production of phosphorus fertilizers from phosphate rock [4; 5], the metal content in phosphate fertilizers may increase with the depletion of high quality phosphate rock in the world [6], and the potential of phosphorus fertilizer to increase the amount of heavy metals in soils is considered as an environmental concern [7]. When 1 ton of phosphorus fertilizers such as superphosphate and TSP are applied to the soil, Cu (20-138 g $ha^{-1}$), Zn (55-235 g $ha^{-1}$), Pb (3.13-17.4 g $ha^{-1}$), Ni (19.2-44.2 g $ha^{-1}$) are added to the soil [8]. Total Cu (0.2-1170 mg $kg^{-1}$), Zn (15.81-1450 mg $kg^{-1}$), Pb (3-225 mg $kg^{-1}$) and Ni (0.5-151 mg $kg^{-1}$) in phosphorus fertilizers; total Cu (3-93.5 mg $kg^{-1}$), Zn (96.3-424 mg $kg^{-1}$), Pb (3.3-240 mg $kg^{-1}$) and Ni (<0.25-35 mg $kg^{-1}$) in micronutrient fertilizer; total Cu (12-50 mg $kg^{-1}$), Zn (1.3-25 mg $kg^{-1}$), Pb (60 mg $kg^{-1}$) in pesticides were determined [7; 8; 9; 10; 11; 12; 13; 14; 15].

In a previous study; the determination of high amounts of total Cu, Zn and Pb in agricultural soils compared to the References soil was the result of long-term application of high amounts of fertilizers and pesticides-fungicides. Phosphorus and potassium fertilizers were identified as the main source of anthropogenic effect in the soil since Cu, Zn, Pb, P and K were in the same principal component and group according to principal component and cluster analysis [16].

In our study, soil samples were taken from depth of 0-20 cm of apple orchards and leaf samples were also taken from the trees. In order to evaluate the behavior, mobility, bioavailability and phytotoxicity of Pb and Ni elements in the soil, total and available Pb and Ni as well as seven geochemical fractions of Pb and Ni (water soluble and exchangeable, bound to carbonates, bound to Mn oxides, bound to amorphous Fe/Al oxides, bound to crystalline Fe oxides, bound to organic and sulfides, residual fractions) were determined using sequential extraction and compared with control samples. Additionally, the relationship of Pb and Ni with available P, Cu and Zn in the soil, their relative distribution among fractions evaluated. To assess the degree of soil contamination, pollution indices such as Enrichment Factor (EF), Contamination Factor ($C_f$), Bioaccumulation Factor (BAF) were determined.

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# Intensified Production of Hydroxyl Radical from Iron-Manganese Synergistic Coupling during Soil Oxygenation: Driven by Iron-Induced Manganese Redox Cycling and Peroxo Complex Formation

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## ABSTRACT

Iron (Fe)-driven biogeochemical processes are central to the production of reactive oxygen species, particularly hydroxyl radicals (•OH), under redox-fluctuating conditions in soil. Although Fe and manganese (Mn) frequently coexist in soils, their coupled effects on •OH generation remain poorly understood. This study revealed previously unrecognized synergistic interactions between Fe and Mn that significantly enhanced •OH production during soil oxygenation, as demonstrated through both soil microcosm incubation and mineral model experiments. In the soils enriched with Fe and Mn, substantial •OH accumulation (19.8-325 μM) was observed, with Fe(II) and Mn(II)/Mn(III) identified as primary electron donors. Scavenging experiments showed that the combined contribution of Fe and Mn to •OH generation exceeded 100%, confirming their synergistic interaction. This synergism was further demonstrated in mineral systems containing both reduced Fe oxides and Mn oxides, where •OH accumulation surpassed theoretical additive values by 61.8%, and electron utilization efficiency measured via ABTS+• increased nearly threefold. Wet chemical analysis, electron microscopy, and in situ Fourier transform infrared spectroscopy collectively elucidated that Fe(II)-driven regeneration of Mn(II)/Mn(III) facilitated the production of $O_2^{\bullet-}$, the precursor species of •OH, while atomic-scale Fe and Mn proximity induced the formation of Fe-O-O-Mn peroxide complexes—both mechanisms synergistically enhancing •OH accumulation. The •OH generated via Fe-Mn synergism further mediated the oxidative transformation of soil organic carbon, copper sulfide, and organically bound copper. These findings unveil a novel natural pathway for •OH production under redox oscillations, and underscore the critical yet overlooked role of Fe-Mn coupling in soil biogeochemical cycles.

# Bioremediation Mechanism of Polycyclic Aromatic Hydrocarbon Contaminated Soil Based on Signal Molecular Regulation Strategy under Low Temperature Stress

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**ABSTRACT**

As persistent organic pollutants, the degradation and mineralization efficiency of Polycyclic Aromatic Hydrocarbons (PAHs) further decrease in low-temperature environments, leading to significant accumulation of PAHs in soil. However, their toxicity mechanisms remain unclear, and the biodegradation mechanisms and remediation strategies for these pollutants under low-temperature stress are not well defined. This study aims to analyze the natural degradation efficiency and pathways of PAHs under low-temperature conditions, assess their toxic mechanisms on plants and soil microorganisms, detect the types of signaling molecules produced during the bioremediation process of contaminated soil, and elucidate the mechanism of interkingdom transduction of these signaling molecules and their mediated bioremediation mechanism for contaminated soil under low-temperature stress.

The study found that the ecological toxicity of PAHs to soil under low-temperature stress primarily involves oxidative stress, inhibiting plant growth and microbial metabolic activity. The combined application of synthetic microbial communities and plants demonstrated significant pollutant removal effects, effectively removing 83% of PAHs from the soil under low-temperature stress. This remediation process alleviated the oxidative stress caused by PAH contamination, lifted the inhibition of PAHs and the low-temperature environment on plant and microbial metabolic activities, ultimately achieving simultaneous PAH removal and restoration of the soil ecosystem. Further research revealed cross-feeding and communication among the functional degrading bacterial consortia. This interaction promoted PAH degradation and biofilm formation, further enhancing energy production and stress responses in the functional bacteria. As PAHs degraded, mediated by the LasI/LasR quorum sensing system, the T6SS system, and serine metalloproteases, the interaction among functional microorganisms shifted from cooperation to competition. This shift could provide more niche space for indigenous microorganisms involved in nutrient cycling, effectively restoring the ecological multifunctionality of the PAH-contaminated environment. The aforementioned research provides innovative strategies for PAH degradation and ecological restoration from the perspective of microbial interkingdom signaling.

**Keywords:** Polycyclic aromatic hydrocarbons (PAHs); Synthetic microbial community; Signaling molecule; Quorum sensing; Contaminated soil remediation

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# From Collieries to Continents: Deciphering the Soil-Pollutant Nexus in Coal Mine Landscapes

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**ABSTRACT**

Coal mining leaves a deep and lasting geochemical footprint on soil systems, yet a global synthesis of pollutant concentrations has been lacking. The meta-analysis by Alekseenko et al. (2025) establishes the first global References concentrations for chemical elements in coal mine soils, derived from a systematic review of 95 studies encompassing 13,925 soil samples across 55 coal fields in 32 countries. The resulting dataset provides mean concentrations for 41 elements, total organic carbon (TOC), and total rare-earth elements (∑REE).

Our findings reveal that coal mine soils are significantly enriched in specific pollutants compared to global pristine soils. The highest enrichment factors are for As, Bi, Hg, Sb, and Se, i.e., elements classified as coalphile, indicating their strong affinity for coal during geologic formation. This demonstrates that the geochemical signature of mined coal is a primary driver of soil contamination. Furthermore, TOC was 1.24 times higher than the global average, a misleading indicator of fertility likely driven by coal dust rather than humus formation. The calculated global References levels serve as a critical benchmark for risk assessment and policy. For instance, the global mean arsenic content (15.9 mg/kg) in coal mine soils exceeds the industrial soil screening levels of Canada, Russia, and the USA, highlighting a widespread ecological risk.

As the world's leading coal producer, China is represented through over 8000 soil samples from the coal basins and coalfields of Bayanhuxu-Eren, Beijing, Huainan, Junggar, Lianxing-Qujiang, Ordos, and South Yellow Sea. The calculated mean concentrations for key pollutants like arsenic do not exceed the global average. However, certain sites exhibit extreme anomalies, such as mercury and cadmium hotspots linked to other industrial and agricultural activities. When benchmarked against the Chinese Environmental Quality Standard for Soils, the average national-scale data for coal mine soils shows safe levels.

The global References values are essential for: (1) distinguishing site-specific pollution patterns from global trends, (2) predicting pollutant burdens in prospective mining areas, and (3) informing soil remediation guidelines and land-use planning in post-mining landscapes. This continental-scale deciphering of the soil-pollutant nexus provides a tool for soil scientists and environmental managers addressing the legacy of coal extraction.

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# Microbial Methylation of Mercury Mediated by Soil Organic Matter: Progress and Prospects

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## ABSTRACT

Methylmercury (MeHg), due to its bioaccumulation and neurotoxicity, is a global concern affecting soil and human health. Soil MeHg is usually produced via methylation of inorganic mercury (Hg) by microorganisms possessing *hgcAB* gene pairs. Microbial methylation of inorganic mercury is strongly mediated by soil organic matter (SOM) through affecting Hg species, the community structures of Hg methylators as well as their interactions with non-methylators. SOM regulates soil Hg species mainly through reduction or complexation pathways, depending on the properties of SOM such as electron donating capacity and sulfur species (Xing et al., 2025). Hg complexed by SOM is available for microbial uptake and methylation. Recent studies found that, in addition to their binding constants, the configuration of SOM-Hg complexes plays an important role in affecting microbial Hg methylation (Liang et al., 2023). Meanwhile, Hg methylation efficiency differs among Hg methylators owing to their differences in cell surface properties. The dominant Hg methylators in soil are usually shaped by SOM via functioning as carbon and energy sources (Pu et al., 2025). An intriguing point is that SOM metabolism by non-methylators can likely fuel Hg methylation by methylators. For instance, ester sulfate within SOM may be catabolized to produce sulfate, which in turn can promote the growth of the Hg methylators thus increasing the production of MeHg (Pierce et al., 2022). However, the detailed mechanisms governing the interactions between Hg methylators and non-methylators remain unclear. Taken together, we will try to summarize current understandings of microbial Hg methylation mediated by SOM and propose some knowledge gaps for better controlling soil MeHg production and its risk.

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# From Pollution to Solution: Microbial Insights and Novel Bacteria for Biodegradation of Organochlorine in Coastal Wetland Soil

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**ABSTRACT**

Chlorinated organic pollutants (COPs) are common pollutants in flooded environments. To examine the residual status and effects of COPs on flooded soil, we first applied a meta-analysis of COPs around the world, including 25 kinds of COPs from 977 sites. Results indicated that COPs were globally detected. The environmental risk of COPs on wetlands soil was higher than in other flooded environments.

We further surveyed 7 coastal wetlands soil in Zhejiang, East China. Gamma-HCH and o,p'-DDT posed the greatest risk. Samples with higher COP pollution had higher microbial diversity, more complex microbial networks, more deterministic community assembly processes and lower microbiome stability. Further analysis using quantitative real-time PCR suggested COP degradation interacted with natural redox processes. Non-obligate organochlorine-degrading bacteria (ODB) might play a significant role in the degradation process of COPs

Thus, we try to isolate ODB from these wetland soil samples. 4 strains were isolated and first demonstrated for γ-HCH degradation. They were identified as *Petrimonas sulfuriphila* PET, *Robertmurraya* sp. CYTO, *Hungatella* sp. CloS1 and *Enterococcus avium* PseS3, respectively. The residual γ-HCH concentrations were 58.8% (PET), 45.6% (CYTO), 60.2% (CloS1), and 69.3% (PseS3) of its initial value, respectively. They are generalists and non-obligate ODB. Genomic analysis indicated that each strain harbours genes annotated to the pathway of halogenated organic matter degradation (e.g. 2-haloacid dehalogenase) and cobalamin biosynthesis. The co-localization of these functional genes with horizontal gene transfer fragments was also identified. Cobalamin and 2-haloacid dehalogenase are involved in γ-HCH degradation. Horizontal gene transfer might facilitate the adaptation of the microbe. Together, these findings provide novel insights into improved bioremediation strategies for COP-polluted soil based on generalist ODB.

**Acknowledgments**

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# Mapping soil deposition of antibiotics at municipality-scale in Brazil

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**ABSTRACT**

Antibiotic use in livestock production is increasingly scrutinized due to risks of soil contamination, selection of antimicrobial resistance, and trophic transfer. Yet, national-scale spatial patterns of soil deposition remain poorly characterized, limiting targeted mitigation. This study presents a first-approximation framework to estimate and map annual soil deposition of veterinary antibiotics across Brazilian municipalities. We compiled 2023 livestock inventories for 5,298 municipalities and combined them with literature-derived consumption coefficients and average live weights. A generic degradation/deposition factor was applied to translate use into potential soil loads. Cattle, swine, and poultry accounted for >97% of estimated deposition, yielding a national load of 4,769 t year$^{-1}$, with relative contributions of 85.6%, 12.2%, and 2.2%, respectively. Although poultry accounts for the largest number of animals, their comparatively low body mass results in only 2.2% of total antibiotic deposition, while swine contribute 12.2% and cattle 85.6%. Regional total antibiotic loads corresponded to 28, 23, 21, 16, and 13% in the Mid-West, North, Southeast, South, and Northeast regions. Because municipal-level livestock data, antibiotic-use coefficients, and deposition parameters vary in quality and completeness, the resulting maps must be interpreted with caution. Municipalities in highly intensive production regions such as Santa Catarina and Paraná may be underrepresented. These states have vertically integrated poultry and swine industries in which detailed farm-level information is commercially sensitive; as a result, production data are commonly reported only in grouped or averaged forms across wider administrative units rather than at municipality level. This reduces the spatial precision of official inventories and can obscure local hotspots. Consequently, some mismatches between expected and mapped deposition patterns likely reflect limitations in data resolution rather than true environmental differences. Despite these uncertainties, the framework provides an operational baseline for national-scale assessments and can support future integration with molecule-specific usage data, biome sensitivity layers, and uncertainty propagation analyses. This approach is replicable for other countries and can help build harmonized global evaluations of soil exposure to veterinary antibiotics.

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# Overlooked Ecological Risks of Chlorinated Pollutants in Anaerobic Soils: Coupling Microbial Dehalogenation with Methanogenesis

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## ABSTRACT

Chlorinated organic pollutants (COPs), encompassing legacy pesticides as well as emerging compounds, persist in soils worldwide, exerting subtle yet profound environmental risks at trace levels. A pivotal but underappreciated facet of their environmental fate is the interplay between their dominant degradation process—microbial reductive dehalogenation—and other redox pathways, such as methanogenesis, which can amplify ecological impacts in anaerobic settings. This study adopts a multi-scale strategy, spanning national soil surveys to targeted microbial consortia, to elucidate this coupling.

A comprehensive nationwide survey of 278 soil samples from seven habitats in China uncovered ubiquitous COPs contamination, with 100% detection rates for key groups like DDTs and HCHs. Residue levels averaged 103.03 ng $g^{-1}$, sustained by both historical legacies and ongoing inputs. Notably, anaerobic soils (e.g., paddies and wetlands) displayed elevated ecological risks (89.1% moderate risk) relative to aerobic counterparts (90.8% low risk), correlating with higher methane emission potentials and underscoring how COPs may exacerbate greenhouse gas fluxes.

Quantitative PCR (qPCR) profiling of organohalide-respiring bacteria (OHRB) across these soils revealed their prevalence, especially in waterlogged anaerobic environments ($10^6$–$10^8$ gene copies $g^{-1}$ dry soil). Microcosm assays with lindane (γ-HCH) as a proxy pollutant confirmed a synergistic dehalogenation-methanogenesis dynamic: degradation rates correlated strongly with dehalogenase (rdhA) gene abundance ($R=0.90$, $P<0.001$), while methane yields rose in tandem ($R=0.81$, $P<0.001$). This indicates that OHRB communities not only attenuate COPs but also potentially intensify methane production, posing dual challenges for pollution remediation and climate goals.

Mechanistic insights from synthetic co-cultures of the obligate dechlorinator *Dehalococcoides mccartyi* (Dhc) and methanogen *Methanosarcina barkeri* (Met) illustrated this syntrophy: the pair achieved >98% lindane removal within 10 days, yielding 14.56 mmol $CH_4$. Met's provision of cobalamin to Dhc and $H_2$ scavenging enhanced dehalogenation efficiency while modulating carbon cycling, highlighting how microbial partnerships can balance pollutant fate with biogeochemical outcomes.

In conclusion, this research underscores the critical need to consider the ecological risks of COPs, particularly in anaerobic soils where their persistence and interaction with methanogenesis can exacerbate environmental challenges. Our findings provide a foundation for developing targeted bioremediation strategies that not only enhance COP removal but also mitigate greenhouse gas emissions, contributing to the "One Health" paradigm.

**Key Words:** Chlorinated organic pollutants (COPs), Ecological risk, Reductive dechlorination, Methanogenesis, Microbial interactions, Anaerobic soil

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# Enhanced Fomesafen Microbial Degradation in Anaerobic Soils by Glucose: Degradation Characteristics Under Different Redox Conditions

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**ABSTRACT**

Fomesafen (FSA), a widely applied diphenyl ether herbicide, frequently contaminates soils by agricultural application, yet its anaerobic fate in soils remains poorly resolved. This study systematically evaluated FSA biodegradation under five environmentally relevant anaerobic redox conditions—nitrate, $MnO_2$, Fe(III), sulfate, and bicarbonate (methanogenic)—using microcosms constructed from deep soil. Paired treatments with and without glucose (1 mM) assessed the extent of co-substrate stimulation. FSA remained stable in sterile controls, confirming negligible abiotic loss. In active microcosms, degradation was strongly redox-dependent. Fe(III)-reducing conditions supported complete FSA removal within 140 days, and glucose addition accelerated transformation dramatically, achieving full removal within 18 days, reducing the half-life from 36.9 to 2.5 days. Sulfate- and bicarbonate-reducing systems displayed moderate removal (49.9–53.8%), while $MnO_2$-supported degradation was limited (14.4%). Glucose significantly enhanced all three systems, increasing removal efficiencies to 55.9–90.3%. Nitrate-reducing microcosms exhibited negligible transformation (<5%), with only minor enhancement upon glucose addition. These findings demonstrate that Fe(III)-reducing conditions represent a dominant anaerobic pathway for FSA degradation in groundwater and that co-substrate stimulation can greatly improve biodegradation rates. The study provides critical insight into the natural attenuation potential and informs the development of targeted redox-based bioremediation strategies for FSA-contaminated soils.

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# Elevated $CO_2$ enhanced PFOA removal and reduced $N_2O$ emissions in soil: evidence from a FACE experiment

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**ABSTRACT**

As a representative newly emerging pollutant, perfluorooctanoic acid (PFOA) with high environmental persistence and resistance to degradation, poses serious risks to soil ecosystems and human health under ongoing climate change. The increasing concentration of $CO_2$ in the atmosphere is perturbing the global nitrogen cycle, altering soil properties and associated microorganism. However, the impact of elevated $CO_2$ ($eCO_2$) on the residues of PFOA and nitrogen cycle in contaminated soil is insufficiently understood. Here, a free air $CO_2$ enrichment (FACE) system was used to evaluate defluorination, nitrogen cycle and related microbial communities in response to $eCO_2$ (ambient $CO_2$ concentrations + 200 μmol $mol^{-1}$). Our results demonstrate that $eCO_2$ significantly decreased the residues of PFOA (by 15.2-28.1%). The relative abundance of organohalide-respiring bacteria (OHRB, e.g. *Dehalococcoides, Desulfitobacterium*, *Desulfovibrio*, and *Anaeromyxobacter*) were significantly increased by $eCO_2$, indicating the enhanced defluorination effects induced by $eCO_2$. Besides, exposure to $eCO_2$ led to reductions in the concentrations of $NH_4^+$-N and $NO_3^-$-N and in the abundances of nitrogen cycle-related genes (Bac-*amoA*, Arch-*amoA, nirS*, *nirK* and *nosZ*), which simultaneously alleviate the competitive inhibition on OHRB and restrict the substrate availability for nitrification and denitrification, thereby suppressing $N_2O$ emissions. Bac-*amoA* gene copies showed a strong and significant negative correlation with PFOA degradation rate ($p < 0.05$). SEM also showed PFOA degradation exhibited notable positive feedback on nitrogen cycle ($p < 0.001$). Overall, this research preliminarily revealed that PFOA removal was promoted and nitrogen cycle may be associated with reductive defluorination under $eCO_2$, providing new insights into the interactions between defluorination and elemental cycle under climate change.

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# Enzyme Activity and Biological Quality Scores in Tropical Soils Exposed to Cadmium and Chromium

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**ABSTRACT**

Soil enzymatic activities and organic carbon (C) and nitrogen (N) pools are fundamental indicators of microbial functioning and nutrient cycling, providing an integrated assessment of soil health under both natural and disturbed conditions. Despite their global importance for C-storage and food production, tropical soils remain understudied with respect to their biochemical sensitivity to heavy metal contamination and the extent to which land-use and management practices modulate this response and impact on soil health. Soils from three contrasting land-use systems (native forest, conventional crop rotation, and crop rotation with diversified cover crops) were incubated for 45 days under Control, Cd (3 mg $kg^{-1}$), and Cr (150 mg $kg^{-1}$) treatments. Phosphatase, arylsulfatase, urease, and β-glucosidase activities were determined by colorimetric assays, while organic C and total N were measured by dry combustion. All indicators were integrated into a Biological Soil Quality Score to compare management-specific resilience. Enzymatic responses reflected land-use effects rather than metal addition. Short-term responses showed that soil management, rather than Cd or Cr addition, governed biochemical behavior: neither metal altered enzyme activities or C and N pools, suggesting low bioavailability and strong buffering typical of highly reactive tropical soils reach in Fe- and Al-hydroxides. Native forest exhibited the greatest phosphatase, arylsulfatase, and urease activities, reflecting intense P, S, and N mineralization in unfertilized, nutrient-limited (oligotrophic) conditions. Conversely, the most biodiversity system (regenerative agriculture) showed the highest β-glucosidase, reflecting stronger cycling of labile C; while conventional crop rotation had the lowest phosphatase and arylsulfatase activities, consistent with reduced enzymatic demand under fertilization. Despite higher enzyme activities and C contents, except for β-glucosidase, the native forest (0.15) showed the lowest Biological Soil Quality Score, whereas agricultural systems (conventional crop rotation - 0.84 and crop rotation with diversified cover crops - 0.86) scored much higher due to greater mineral nutrient inputs and markedly lower acidity from liming. Overall, the results demonstrate that enzyme profiles must be interpreted considering resource constraints and management history, as elevated activity can denote compensatory response rather than enhanced soil condition.

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# Micro-scale redox heterogeneity governs chromium mobility and reoxidation in flooded industrial soils with contrasting properties

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**ABSTRACT**

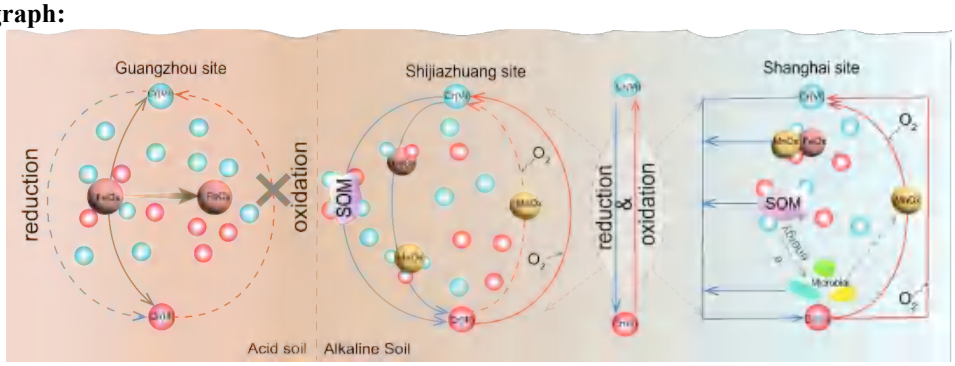
Rising sea levels and climate change are intensifying soil flooding and altering redox dynamics, profoundly influencing chromium (Cr) behavior in contaminated industrial soils. Here, we combined *in situ* techniques, including high-resolution diffusive gradients in thin-films (HR-DGT) and planar optodes (PO), with *ex situ* incubation to unravel the transformation and availability of Cr in different industrial soils under both short-term and long-term flooding. Results showed that soil physicochemical properties strongly governed oxic-anoxic microzone (<3 mm) formation and redox-driven Cr availability. In acidic soils characterized by low soil organic matter (SOM) and amorphous Fe oxides (Ox-Fe), limited Cr(VI) reduction led to high labile Cr(VI) concentrations even under prolonged flooding. Conversely, high SOM and Ox-Fe in alkaline soils promoted significant Cr(VI) reduction and stabilization. However, the potential for Cr(III) reoxidation was confirmed at oxic-anoxic microzones in MnOx-rich alkaline industrial soil, where microbial activity further intensified redox transformations. Specifically, higher 16S rDNA copy numbers and abundances of Cr-related bacteria genera (e.g., *Sphingomonas* and *Lysobacter*) were found in soils facilitating Cr transformation. This study provides a mechanistic framework for predicting Cr behavior in flood-prone industrial soils and highlights the need for site-specific management strategies under climate change impacts.

**Keywords:** HR-DGT, planar optodes, anoxic-oxic interfaces, soil properties, microbial activity

**Highlights:**

a) Coupled HR-DGT and planar optodes revealed in situ Cr redox heterogeneity.
b) Acidic soils with low SOM maintained high mobile Cr(VI) under flooding.
c) MnOx-rich alkaline soils triggered Cr(III) reoxidation at oxic-anoxic microzones.
d) Microbial communities intensify redox-driven Cr transformations and mobility.
e) Soil properties governed Cr availability under varying flooding durations.

**ABSTRACT graph:**




(Cr availability and transformation in the three industrial soils. The red and blue lines refer to oxidation and reduction respectively.)

**Acknowledgments**

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# Elucidating Arsenic–Soil Mineral Interactions at the Microscopic Interface: Insights into Arsenic Geochemistry based on mechanistic speciation

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**ABSTRACT**

The interplay between inorganic arsenic (As) and soil minerals is critical for predicting As geochemical processes. However, our understanding of the reactive mineral interfaces and the microscopic interaction mechanisms of As in soils remains limited. Here, by integrating multiple characterization techniques and focusing on microscopic interfacial speciation, we successfully elucidated the interactions between As and two representative minerals—ferrihydrite and silicate clay minerals. Batch adsorption experiments revealed an apparent contradiction between the adsorption affinity and capacity of As(III) and As(V) on ferrihydrite. We demonstrate that As(III) forms predominantly monodentate complexes at high loadings, whereas As(V) consistently forms bidentate complexes. Consequently, although As(III) exhibits weaker binding strength, it occupies more surface sites and therefore displays lower affinity but higher adsorption capacity (*Figure 1*) [1]. Component extraction and adsorption experiments showed that clay minerals exhibit substantial adsorption of As—contrary to common assumptions that net negative charged clay minerals should have been ignorable regarding the adsorption of As. We conclude that, despite electrostatic repulsion on basal surfaces, hydroxyl groups on edge surfaces can form hydrogen bonds and covalent bonds with oxyanions, indicating a non-negligible contribution of clays to As retention (*Figure 2*) [2]. Our study further identified the key reactive surfaces controlling As adsorption in soils and, elucidated how microscopic speciation governs macroscopic behavior. This bottom-up, mechanistic approach provides fundamental insights into the environmental behavior of As.

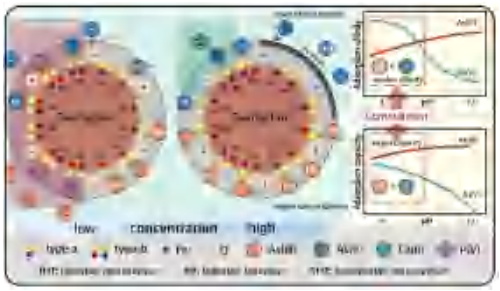



Figure 1 Mechanistic interpretation of As adsorption on ferrihydrite based on surface speciation[1]

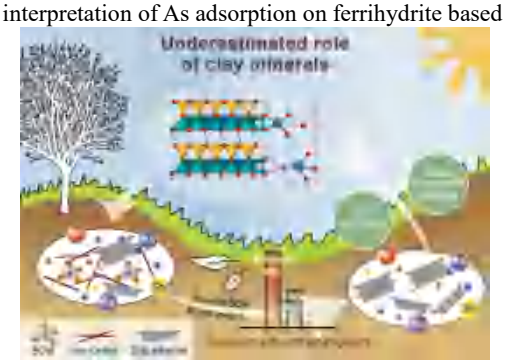



Figure 1 Revising the current understanding of oxyanion adsorption by clay minerals[2]

**Acknowledgments**

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# Microbial Degradation of Soil Microplastics (MPs) Related to Greenhouse Gas Emissions

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**ABSTRACT**

Microplastics (MPs) pollution and greenhouse gas (GHG) emissions are two significant global environmental issues. While microorganisms are central to MPs degradation, their specific response to environmental stress in unique soil ecosystems (e.g., saline-alkali land) and the subsequent regulatory mechanisms over GHG emissions remain poorly understood. This work deciphers the link between microbial-mediated MPs degradation and soil GHG emissions, particularly under such stressed conditions. Results demonstrate that MPs function as an exogenous carbon substrate, enhancing GHG emissions. Their degradation reshaped the native microbial community structure and actively interfered with soil carbon and nitrogen cycling processes. These findings highlight microbial degradation of MPs as a critical driver in regulating GHG emissions from terrestrial environments.

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# Multi-Omics Metabolic Models of Coupled Dechlorination and Methanogenesis Enhance Pollution and Carbon Reduction in Anaerobic Soils

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**ABSTRACT**

Efficient bioremediation of chlorinated organic pollutants (COPs) under anaerobic soil is often constrained by concurrent methane production, posing a trade-off between pollutant removal and greenhouse gas mitigation. Here, we present a digital-driven framework that integrates pure/co-culture experiments, multi-omics comprehensive databases, and genome-scale metabolism-expression modeling to rationally design microbial consortia for COPs remediation.

We focused on orchestrating interactions among key microorganisms: obligate dechlorinating bacteria (Dhc), methanogens (Met), and facultative dechlorinators, including iron-reducing bacteria (Geo) and sulfate-reducing bacteria (Dsv). Dhc displayed limited yet stable dechlorination activity and showed dependence on essential metabolites supplied by its partner strains. The Dhc-Met consortium demonstrated high pollutant removal efficiency and carbon-reduction potential. Incorporation of Dsv or Geo with Dhc further enhanced synergistic interactions, enabling directed metabolite and electron flow toward dechlorination pathways. Notably, the Dhc-Met-Dsv community achieved high dechlorination rates with minimal methane accumulation via combined direct interspecies electron transfer (DIET) and complementary metabolic exchanges. Under lactate-fed conditions, the four-member consortium sustained efficient dechlorination and methane suppression through competitive carbon utilization and metabolic complementarity. Key metabolites (e.g., cobalamin, cysteamine), electron carriers, and environmental factors (carbon sources, sulfate, hydrogen partial pressure) were identified as critical regulators of community function.

This study provides a theoretical basis and new perspectives for developing precision bioremediation strategies for COP-contaminated soils. It also contributes to advancing sustainable environmental management under the “dual-carbon” goals.

**Acknowledgments**

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# Neglected contributions of residual herbicides at various levels on soybean root rot: links with time-series changes in non-target soil microbial communities and functions

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## ABSTRACT

Residual herbicides persist widely in soybean-producing soils and may disrupt rhizosphere microbial communities underlying plant health. However, their combined impacts on soilborne disease dynamics remain poorly understood. In this study, pot experiments together with supporting microbiological tests were used to examine how different levels of combined herbicide residues influence microbial communities, core microbial taxa, microbial functions, and the development of soybean root rot. Combined herbicides at high residual level negatively affected soybean growth and significantly contributed to soybean root rot ($P < 0.05$). Microbial complexity and stability were significantly reduced by herbicides at moderate and high levels, conducive to pathogen invasion. The typical pathogens of *Fusarium* spp. exhibited as the keystone taxa in microbial networks or significantly ($P < 0.05$) enriched in treatments with herbicide residues. Additionally, we highlight the importance of core microbial taxa by tracking rhizosphere microbial changes across different time points. Herbicide stress increased root rot severity, with elevated DSI evident from the early seedling stage (5-7d) and persisting throughout the period. Notably, herbicide-induced changes in core taxa on days 5-7 significantly ($P < 0.05$) correlated with final disease severity. Herbicide stress reduced key disease-suppressive functions (biosynthesis of macrolides, enediyne and vancomycin group antibiotics, and siderophore group nonribosomal peptides), which mechanistically explained DSI variation. These functions were linked to the identified core taxon Streptomyces. These findings provide improved evidence regarding the effect of combined residual herbicides on soybean root rot, with direct facilitation at high level and potential contributions at low and moderate levels. Importantly, days 5-7 was a sensitive period when herbicide stress disrupted core microbial taxa and promoted disease development. Therefore, maintaining the abundance and stability of core taxa during this period is important, even under low-herbicide stress. This study highlights the often-overlooked effects of herbicides on soil and plant health, and the key role of early core taxa in shaping plant–pathogen interactions under herbicide stress. These findings offer useful insights for developing microbiome-based strategies to improve plant protection in sub-healthy agricultural soils.

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# The SIMULATE Project: evaluating climate-warming impacts on metalliferous mine tailings to guide restoration strategies in semiarid landscapes

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## ABSTRACT

Metalliferous mine tailings are among the most challenging terrestrial environments due to their high concentrations of metal(loid)s, lack of organic matter and nutrients, poor soil structure and, in some cases, extreme pH and high salinity. Conventional restoration strategies usually rely on topsoil capping and revegetation, but their long-term sustainability in semiarid regions has been questioned. Alternatively, phytomanagement approaches based on the direct growth of plants on mine wastes are increasingly considered nature-based solutions capable of promoting functional soil-plant systems through the formation of fertility islands. However, little is known about how restored and spontaneously colonized tailings respond to global warming in terms of functionality and ecotoxicological risks, which is essential to evaluate the suitability of phytomanagement versus conventional restoration under current and future climate scenarios.

The SIMULATE project aims to assess how and to what extent conventionally restored (capping and revegetation) and spontaneously colonized metalliferous mine tailings from Mediterranean semiarid areas respond to warming, relative to natural surrounding soils. To achieve this, warming conditions are experimentally forced in the field by installing open-top chambers (OTCs) in shrubland patches. The greenhouse effect inside the OTCs increases air and surface soil temperatures, enhancing evapotranspiration and inducing soil dryness and plant stress. Physical, physicochemical and biological soil parameters related to ecosystem functionality are being monitored over a 2-year period, allowing successive seasonality to stimulate system responses to forced warming. Monitoring includes key biological indicators such as $CO_2$ emissions, organic matter decomposition, enzyme activities, microbial metabolic activity and phylogenetic composition, and invertebrate feeding activity and microarthropod community structure. Multigenerational ecotoxicity bioassays with soil invertebrates will be performed under controlled conditions that mimic the field warming treatments, enabling a comprehensive assessment of potential risks. SIMULATE will generate essential knowledge on the sensitivity of tailing soil-plant systems to climate warming and on the performance of nature-based phytomanagement strategies relative to conventional technical restoration. The results will support improved planning, management and restoration of metal-polluted environments in semiarid regions under present and future climate conditions. The poster presents the outline of the project.

**Acknowledgments**

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# Rethinking Restoration: Functional Trajectories of Soil-Vegetation Systems in Restored vs. Spontaneously Colonized Metalliferous Mine Tailings under a Changing Climate

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## ABSTRACT

Metalliferous mine tailings, which store waste from ore processing, are often regarded as barren, biologically impoverished substrates, yet many of them exhibit spontaneous plant colonization and the development of functional soil-vegetation systems. Over the last decade, our research in Mediterranean semiarid tailings, mainly from southeastern Spain, has investigated how management history (conventional capping and revegetation vs. abandonment without restoration and spontaneous colonization over years) shapes the functional and ecotoxicological performance of these systems under current and future climate conditions simulated through combining climate-controlled chambers and in situ warming experiments with open-top chambers. We adopt a holistic approach integrating soil physics and chemistry, multiple biological indicators of system functionality, microbial community attributes, plant functional traits and ecotoxicity tests to understand how the processes observed in spontaneously colonized tailings can inform and support nature-based phytomanagement strategies, and under which conditions these can be a realistic alternative to classical technical restoration.

Our studies show that fertility islands formed by native vegetation in abandoned tailings can attain levels of soil functionality comparable to those of nearby natural areas, despite high total metal(loid) concentrations. These vegetated patches modulate seasonal variability in soil moisture and temperature and act as hotspots of biological activity, enhancing microbial processes and soil-fauna dynamics. The structure and stratification of vegetation emerge as key determinants of medium- and long-term sustainability, but their functional roles in supporting processes such as C and N mineralization, mediated by the dominance of *k*- or *r*-strategy microbial communities, differ between management histories. Ecotoxicity assessments consistently show that biological functioning can be partially decoupled from total metal(loid) concentrations, highlighting the importance of bioavailability, microhabitat buffering and vegetation-driven amelioration. The presence of soil microarthropods is linked to the first stages of spontaneous plant colonization in abandoned tailings, acting as key agents in organic matter turnover and the recovery of ecosystem structure and function.

Overall, this research line provides an integrated, process-based framework to evaluate trade-offs between technical restoration and phytomanagement, and to support evidence-based management of metalliferous mine tailings in a warming, increasingly water-limited world. Together, these findings redefine how tailings are perceived, demonstrating that spontaneous ecological processes can generate functionally resilient soil-vegetation systems whose mechanisms are directly transferable to climate-smart phytomanagement interventions. The presentation will summarize these advances and highlight key knowledge gaps for future research.

# Photochemical characterization of paddy water: Formation of reactive intermediates for micropollutant degradation

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**ABSTRACT**

Although the photochemical behavior of surface water and its effects on pollutant transformation have been studied extensively in recent years, the photochemistry of paddy water remains largely unknown. In this study, we examined the photochemical processes involving paddy water samples collected at four different cultivation stages of rice. Triplet dissolved organic matter (3DOM*), singlet oxygen (1O2), and hydroxyl radicals (•OH) were found to be the dominant reactive intermediates (RIs), and their apparent quantum yields and steady-state concentrations were quantified. Compared with the typical surface water, quantum yields of 3DOM* and •OH were comparable, while quantum yields of 1O2 were about 2.4-6.7 times higher than those of surface water. Fluorescence emission-excitation matrix (EEM) spectra, Fourier transform ion cyclotron resonance mass spectrometry (FTICR-MS), and statistical analysis revealed that DOM properties and nitrite concentration were the main factor influencing RIs generation. The results suggest that DOM with lower molecular weight and humification extent generated more RIs, and nitrite contributed to 23.9%–100% of •OH generation. EEM and FTICR-MS data showed that DOM with more saturated and less aromatic formulas could produce more 3DOM* under the irradiation, while the polyphenolic components of DOM inhibited the formation of RIs. A kinetic model of RIS-induced pollutant transformation in overlying water of paddy field was constructed, and the contribution of RIs to the abiotic transformation of the typical insecticide imidacloprid was investigated. Firstly, the direct photolysis quantum yield of IMD is determined to be 1.05×10-4. The second-order reaction rate constants of IMD with 3DOM*, 1O2 and •OH are 3.77×108 L mol-1 s-1 (kIMD,3AQDS*), 3.78×106 L mol-1 s-1 (kIMD,1O2) and 2.52×109 (kIMD,•OH) L mol-1 s-1, respectively. The primary degradation rates of IMD in overlying water at seedling, tillering and joint stages were 0.024, 0.022 and 0.032 h-1, respectively. The steady-state concentration of RIs in water samples and the reaction rate of RIs with IMD determined the contribution of RISs to IMD degradation. Kinetic calculation determined that 3DOM* was the main active component (88-92%) that promoted the degradation of IMD. Further, a kinetic model was used to predict the photodegradation process of IMD in rice water under different environmental conditions according to the water photochemical parameters of rice and IMD photoreactivity of different RIs. DOM and NO2- concentrations determined the dominant position of 3DOM* and •OH, respectively. In addition, the degradation rate of IMD decreased gradually with the growth of rice. Product analysis showed that the primary denitrification intermediate was highly toxic, but further oxidation reduced its toxicity. The cleavage and ring-opening products are smaller in size than other intermediate molecules and are easily degraded in rice fields, but harmful to aquatic animals. The hydroxylation pathway related to 3DOM* and •OH is the detoxification process of IMD. This study provides new insight into the pathways of micropollutant abiotic transformation in paddy soil and water.

**Acknowledgments**

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# Risk Assessment of Agricultural Plastic Film and Microplastics in Soil-Water Systems: Fate, Transport, and Ecological Implications

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## ABSTRACT

Soil and water pollution pose a major environmental challenge in China. Emerging contaminants like agricultural plastic films, their additives, and microplastics (MPs) are of growing concern, yet critical gaps remain. These include inadequate monitoring, unclear pollution levels, poorly understood environmental processes and risks, and ineffective conventional controls—all compounded by their complex, multi-process-driven fate in the environment.

This research systematically assessed the environmental behavior and risks of plastic-associated pollutants across agricultural and wetland systems. For agricultural films, suspect screening and modelling revealed 89 additives, with 62 quantified. Their release, influenced by film properties and environmental conditions, introduces thousands of metric tons of additives like phenolic antioxidants and phthalates into Chinese soils annually, posing a moderate ecological risk and altering soil microbial functions.

Simultaneously, coastal wetlands were identified as key hubs for microplastics (MPs) and co-transported organic pollutants. Field and microcosm studies demonstrated that MP aging is co-driven by photo-oxidation (>55% contribution) and microbial degradation, altering their surface properties. This aging process critically enhances MPs' adsorption capacity for pollutants like γ-HCH while paradoxically inhibiting their microbial degradation. Furthermore, aged MPs perturb sediment microbiomes, amplifying processes such as methane production. The findings underscore that the interactions between additive release, MP aging, and co-contaminants create compounded, system-level risks that challenge conventional single-pollutant assessments

Collectively, our findings underscore the complex, system-level interactions between plastic pollution, contaminant dynamics, and environmental conditions. This integrated perspective is vital for developing refined monitoring strategies, accurate risk assessment frameworks, and targeted mitigation measures for plastic pollution under real-world, multi-stress scenarios.

**Acknowledgments**

This research was supported by the National Science Foundation of China (42225705, 42177006), the Zhejiang Provincial Key Research and Development Program of China (2023C02004), the Fundamental Research Funds for the Central Universities (226-2025-00004), and China Agriculture Research System of MOF and MARA (CARS-04).

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# Microalgae enhance the ameliorative effects of organic materials on soil treated by thermal desorption

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**ABSTRACT**

After thermal desorption treatment, the soil physical structure became worse, the organic carbon content became lower, and the nutrient was unbalanced. Therefore, improving the properties and nutrient cycling capacity of the treated soil is essential for its ecological restoration. In this study, a incubation experiment was conducted on soil treated by the ex-situ thermal desorption of a polycyclic aromatic hydrocarbon (PAH)-contaminated site. Common organic material amendments (e.g., sheep manure and organic fertilizer) and new biofertilizers (e.g., microalgae) were used to investigate the alterations in soil physicochemical properties, microbial community function and microbial community diversity under eight different treatments. The results showed that microalgae increased the ameliorative effects of organic materials on treated soil. In detail, microalgae decreased the mean particle size of soil and significantly increased the content of clay and silt, and changed its particle size distribution. They also significantly increased the contents of soil total organic carbon (TOC), cation exchange capacity (CEC), total nitrogen (TN), nitrate nitrogen ($NO_3^-$-N), available phosphorus (AP), and available potassium (AK), and reduced soil pH, but with no significant effects on electrical conductivity (EC). Furthermore, microalgae significantly altered the microbial community composition and enhanced soil multifunctionality, especially carbon, nitrogen, and phosphorus cycling. Redundancy analyses showed that TN, TK, and TOC were the primary factors explaining the changes in the composition of the main functional microbial community. The findings of this study provide a theoretical basis for soil fertility restoration and structural reconstruction on soil treated by thermal desorption.

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# Quantifying Soil Health in Cd-Contaminated Soil Remediation: Methodology Optimization and the potential role of Soil Viruses

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## ABSTRACT

**[Objective]** Soil health assessment is essential for food security and sustainable agriculture, especially in Cadmium (Cd)-contaminated farmlands. While microbial diversity and activity, including soil virome, are essential for maintaining agroecosystem functions, robust frameworks for evaluating contaminated soil health are still lacking. This work aims to develop and optimize assessment methodologies under Cd remediation and elucidate the potential contribution of soil viruses to soil health enhancement. **[Method]** Soil samples were collected from an in-situ remediation experiment involving three amendment application rates (CK, Low, and High) under rice-soybean monoculture and rotation systems. Soil physical, chemical, and biological properties were measured, and viral communities were characterized by metagenome and metatranscriptome. **[Result]** Soil health was quantitatively evaluated across four dimensions: environmental quality improvement, Cd stress mitigation, microbial diversity maintenance, and ecosystem multifunctionality. Using Principal Component Analysis and correlation analysis, a 10-indicator Minimum Data Set (MDS) was derived from 20 candidates. Among the three scoring approaches, Comprehensive Assessment of Soil Health (CASH) method exhibited the best sensitivity in reflecting Cd-polluted soil health status at the plot scale. Compared to monoculture and untreated controls, rotation and amendment increased the Soil Health Index (SHI-CASH) by 19.6% and 6.9%, respectively. Significant correlations between grain Cd accumulation, crop yield, and SHI-CASH further validates the robustness of the MDS framework. Random Forest analysis identified soil viral parameters, such as Shannon diversity, transcriptional activity, and the relative abundances of *Herelleviridae* and *Autographiviridae* as key predictors of SHI-CASH, with their ecological contribution being more pronounced in dryland ($R^2$ = 44.5%) than in flooded paddy systems ($R^2$ = 12.8%). **[Conclusion]** These findings validate the MDS-CASH framework as a robust tool for evaluating contaminated soil health and reveals that soil viruses are potential overlooked drivers of farmland health recovery.

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# The Passivation Remediation of Weakly Alkaline Cadmium-Contaminated Farmland Soil

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## ABSTRACT

Excessive heavy metals in soil pose a threat to food safety and human health. The research on remediation of heavy metal contaminated soil mostly focuses on acidic soils, while there are still problems such as low attention, mismatched treatment technologies, and outdated research and development technologies for Cd pollution in weakly alkaline soils. This study took weakly alkaline cadmium contaminated soil as the research object, selected materials with good passivation effects, and explored modification methods to improve the passivation ability of materials. And the passivation mechanism and stability of passivation materials on soil Cd were further explored. The research results showed that potassium permanganate/hematite modified biochar, manganese dioxide modified phosphate rock powder, and the combination application of biochar and phosphate rock powder significantly reduced the biological activity of Cd in weakly alkaline soils, promoted plant growth, but would reduce the diversity of soil microorganisms. This study also comprehensively evaluated the effects of passivation materials on soil environment, including soil nutrient availability, enzyme activity, abundance of resistance genes, and microbial communities. The passivation mechanisms of biochar and phosphate powder on soil Cd include precipitation, complexation, oxidation-reduction, ion exchange, and π-electron accumulation. The contribution rates of various mechanisms to Cd passivation need further research.

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# Long-Term Ecological consequences of the Proton Launch Vehicle First Stage Falling: Preliminary Results of the Comprehensive Case Study in Central Kazakhstan

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## ABSTRACT

In Central Kazakhstan, from 119 falling sites of the 1st stage of the Proton launch vehicle (LV launched from the Baikonur cosmodrome) formed since 2001, we selected sites occurred in the most widespread communities of the *Artemisia terrae-albae* formation, including derivative communities formed during pyrogenic succession with a predominance of annuals and/or cespitose grasses within the leveled surfaces of interfluves. Then we divided them into four age groups based on the years elapsed since the stage falling: 0-3(5), 5-10, 10-15 and 15-25 years. The group 1 corresponds to communities dominated by annuals, while the group 4 corresponds to communities recovering and conditionally recovered after the impact. Among these 73 falling sites, we selected (whenever possible) sites with similar age of pyrogenic succession (most of them burned in 2017) to reduce the contribution of pyrogenic dynamics to the state of vegetation, assuming that the combined impact of stage falling would still outweigh the pyrogenic impact. However, subsequent analyses revealed that the combined impact of the Proton LV stage falling, including the pollution with highly toxic heptyl is similar in the environmental impact to the one caused by fire.

During field study in the stage falling sites, we conducted 56 geobotanical descriptions at 100 $m^2$ plots and collected 51 topsoil samples (including 42 paired samples characterizing the impact site and a nearby background area).

Soil turbidity and the abundance of artifacts with characteristic sizes of 2–15 cm suggest formation of Epimahic Technosols (Alcalic, Amphigypsic, Loamic) in the 1st stage falling sites. The area of Technosols within the surveyed impact areas is 0.94 hectares (<0.0006% of the area of the 1st stage falling regions of the Proton LV in Central Kazakhstan).

The soils of all surveyed sites (Gypsisols and Solonetz) are loamy and non-saline. The concentrations of total and mobile (16±7% of the total) heptyl, water-soluble $NO_3^-$, $NO_2^-$, and $NH_4^+$ decrease from recent to older impact sites. But there is no such trend for Ntot content.

The age of the stage impact site significantly influences only the reduction in the projective cover of *Agropyron desertorum* and the slight increase in projective cover of *Stipa sareptana*. Four to eight years after the impact are sufficient for the species composition of plant communities in Central Kazakhstan to recover and approach the state of the background sites. Recovery of structural indicators of the phytocenosis also occurs in most cases within 10 years. However, the manifestations of digression caused by the technogenic impact persist for a significantly longer time in some of the impact sites and slow down the restoration of dominant species of background communities. No significant differences were found between the species composition of the vegetation in the disturbed and background sites. In Central Kazakhstan, two consecutive impacts (a pyrogenic impact not associated with a rocket launch and the impact of the first stage of the Proton LV) decrease the manifestation of the earlier impact on the characteristics of plant communities.

The composition of the soil microbiome in 21 soil samples with the highest heptyl concentrations does not differ in heptyl-contaminated and control soils in terms of α- and β-diversity of bacteria and fungi at all taxonomic levels, nor in their metabolic potential. No reliable indicator taxa of microorganisms responding to the presence of heptyl and its derivatives in soils were found.

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# Analysis of Traits and Prediction of Angiosperm Species of Plant-Hyperaccumulators of 17 Heavy Metals and Metalloids: Initial Results

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**ABSTRACT**

We compiled the database of hyperaccumulator plants using AI and machine learning algorithms, based on information from 18,500 publications indexed in Scopus and plant trait databases. It contains the following information for 1,548 species from 791 Angiosperm genera (hyperaccumulators and non-hyperaccumulators):
-measured concentrations of 80 chemical elements with publication References;
-classification of plant species by their ability to accumulate 17 heavy metals and metalloids (HMMs) (Ag, Al, As, Cd, Ce, Co, Cr, Cu, Hg, La, Mn, Mo, Ni, Pb, Se, Tl, and Zn, as well as REEs) into 5 groups: hyperaccumulators, strong and weak accumulators, neutrals, and deconcentrators;
-morphological, ecological, anatomical, and physiological plant traits.

Of the 1,548 plant species in the database, 675 species hyperaccumulate at least one of the 17 elements examined, and most of the remaining 873 species are strong accumulators. Phylogenetic analysis revealed several clades with a >50% probability of having reduced or increased potential for hyperaccumulation of Cd, Cr, and any HMM. Genera capable of hyperaccumulation do not cluster on the evolutionary tree of Angiosperm, which reflects the mosaic nature of the location of hyperaccumulators on it and indicates the repeated independent emergence of this trait during evolution. The ChiSquared test revealed an uneven distribution of families across hyperaccumulator and non-hyperaccumulator groups for genera that accumulate at least one HMM. The Salicaceae family has the largest proportion of hyperaccumulator genera, the Anacardiaceae and Lauraceae have the smallest.

The detected hyperaccumulation of one element can be a good predictor of hyperaccumulation of others. A comparison of the external traits of hyperaccumulator and non-hyperaccumulator plants did not reveal any features that reliably differentiate these two groups. However, for 28 traits, the mean values for hyperaccumulators and non-hyperaccumulators differed by more than five times. The lack of statistical significance for such differences in mean values is explained by the small number of species for which the trait is known or the high variance of the trait value in both plant groups. Currently, the most applicable criteria for searching for hyperaccumulators of HMMs include:
-the ability to hyperaccumulate another HMM;
-belonging to a clade with increased hyperaccumulation potential according to TreeBreaker;
-belonging to a family with a high proportion of hyperaccumulators in our database.

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# Environmental Prevalence and Application of Organohalide-respiring Bacteria in Remediation

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**ABSTRACT**

Halogenated organic compounds are widely used in industrial and agricultural sectors, but their improper use and disposal have led to global pollution issues, posing threats to ecosystems and human health. Organohalide-respiring bacteria (OHRB) can remove halogens from halogenated organic compounds through reductive dehalogenation, reducing their toxicity and persistence, thereby offering promising prospects for the remediation of contaminated sites. Nevertheless, most known dehalogenating bacteria exhibit high substrate specificity, with each strain capable of reductively dehalogenating only one or a limited class of halogenated organic compounds. However, the pollution sites often contain multiple structurally diverse halogenated organic pollutants. There is an urgent need to discover OHRB capable of simultaneously reductively dehalogenating multiple halogenated organic compounds to advance the remediation of co-contaminated environments.

We first report the widespread distribution of versatile OHRB in a variety of environments and their potential for reductive dehalogenation of halogenated organic compounds. We found that these versatile OHRB may utilize a single multifunctional dehalogenase to reductively dehalogenate different halogenated organic compounds. Through protein structure prediction and molecular docking analysis, we further discovered that multifunctional dehalogenases can dehalogenate different halogenated organic compounds via distinct active sites and amino acid residues. Additionally, we observed that interspecies interactions within microbial communities, biofloc encapsulation, and functional genes related to environmental stress collectively determine the widespread distribution of versatile OHRB in the environment. Based on these findings, we developed multiple remediation methods suitable for co-contaminated environments, including sludge inoculation and nanoscale zero-valent iron–biological synergistic remediation technologies, which effectively enhanced the remediation of various halogenated organic compounds in contaminated soils and water bodies.

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# Literature Data-Driven Prediction of Soil and Groundwater Pollutant Distribution at Regional Scales

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**ABSTRACT**

Machine learning technologies offer an effective approach to overcoming the limitations of traditional analytical methods, enabling efficient prediction of pollution distribution and risks as well as correlation analysis of influencing factors. However, constructing high-quality datasets remains a core bottleneck for their application at large regional scales. Systematic mining of literature-derived data can address the scarcity of regional soil-groundwater sampling data, serving as a powerful tool for characterizing regional groundwater quality patterns. Preliminary achievements have been made in pollution distribution prediction using published literature data. For example, studies on global groundwater arsenic pollution (*Science*, 2020), per- and polyfluoroalkyl substances (PFAS) distribution (*Nature Geoscience*, 2024), and global agricultural soil toxic metal risk assessment (*Science*, 2025) have verified the application potential and value of literature data in large-scale regional pollution research from multiple dimensions. Nevertheless, existing literature data mining has prominent shortcomings: lack of a unified standardized workflow (low extraction efficiency), inadequate quality control system (unreliable data), and poor matching between environmental covariates (soil physicochemical properties) and pollution data. These issues collectively restrict the applicability of literature datasets and compromise the accuracy of subsequent prediction models. To address these critical challenges, this study developed a systematic workflow for soil-groundwater pollution literature data mining. By optimizing extraction rules, establishing multi-dimensional quality control criteria, and improving covariate-pollution data matching mechanisms, the workflow realizes efficient and accurate extraction/integration of pollution concentrations, key environmental parameters, and spatiotemporal information from domain-specific literature. Practical results show that this workflow significantly improves the efficiency and quality of literature dataset construction, providing stable and reliable data support for training large-scale groundwater pollution prediction models. It further offers scientific and effective theoretical and technical References for formulating regional pollution prevention and control strategies.

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# The genesis of nano-colloid-bound Cd and As: from climatic and pedogenic controls to global projections

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**ABSTRACT**

Avoiding the transport of toxic metal ions facilitated by soil-nano-colloids constitutes a critical challenge in agricultural soils, particularly since climate and soil properties contribute to their genesis in an unknown manner, thereby limiting a comprehensive global perspective. Here, we analyzed 105 soil samples collected along a ~3,500 km climatic gradient with two toxic metals of primary concern: cadmium (Cd) and arsenic (As). Results showed that the genesis of nano-colloid-bound Cd and As increases with elevated temperature and precipitation, regulated by pH changes associated with mineral weathering (Cd) and by weathering-induced release of mineral nano-colloids (As). We therefore produced the first global map of nano-colloid-bound Cd and As using deep learning algorithms, revealing higher formation potentials in the eastern compared to the western part of a metal-rich zone in low-latitude Eurasia. Under a high-carbon emission scenario (2.4–4.8°C warming), nano-colloid-facilitated Cd and As transport is projected to rise by 2.7% and 6.1%, respectively. Our findings identify southern North America, southwestern South America, southern Europe, northern and southern Africa, Central Asia, China, and southern Australia as emerging risk regions, and highlight climate-sensitive nano-colloid processes as a key but overlooked component of terrestrial metal cycling under global change.

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# Divergent responses of alfalfa-soil nitrogen cycling to PE and PLA microplastics: A metabolic and microbial perspective

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**ABSTRACT**

Increasing input of microplastics (MPs) into agricultural soils poses a significant risk to soil structural integrity and biogeochemical cycles. However, the cascading effects of MPs on soil elemental composition and subsequent plant physiological responses remain poorly understood. This study investigated the impacts of polyethylene (PE-MPs) and polylactic acid (PLA-MPs) at environmentally relevant concentrations (50 and 500 mg/kg) on alfalfa growth, metabolism, and soil microbial functions. Our results revealed that MP degradation initially increased soil organic carbon but induced nitrogen (N) deficiency, particularly in PLA-MPs treatments (11% decrease in N content). This reduction in soil $NH_4^+$-N triggered a compensatory activation of the phenylpropanoid biosynthesis pathway in alfalfa, leading to the accumulation of signaling flavonoids and coumarins, which subsequently stimulated root nodulation. Specifically, high-dose PLA-MPs (500 mg/kg) significantly promoted nodule formation and biomass accumulation, corroborated by enhanced activities of N-metabolism enzymes; in contrast, PE-MPs exhibited negligible effects. Furthermore, PLA-MPs exposure increased N accumulation and utilization efficiency in roots, with glutamate, aspartate, and total protein contents rising by 26%, 24%, and 16%, respectively. This enhanced symbiotic nitrogen fixation eventually replenished soil nitrogen pools during the later growth stages. Microbial analysis showed that high PLA-MPs concentrations significantly boosted the activities of soil nitrate reductase, protease, and urease, and increased the relative abundance of key taxa (e.g., Proteobacteria, Rhizobiales, and Burkholderiales). Co-occurrence network analysis further highlighted that microbial complexity was inhibited by PE-MPs but strengthened by PLA-MPs. Microbial functional prediction confirmed that key N-cycle processes, including nitrogen fixation and denitrification, were significantly upregulated under PLA-MP treatment. These findings provide critical insights into the divergent ecological risks of conventional and biodegradable plastics, offering a scientific basis for sustainable agricultural management in MP-contaminated soils.

**Key words:** Microplastics; Nitrogen cycling; Soil; Alfalfa; Rhizosphere microorganisms; Emerging contaminants

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# Inhibition mechanism of hexachlorocyclohexane isomers on different methanogen metabolism

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**ABSTRACT**

Hexachlorocyclohexane (HCH) is classified as a persistent organic pollutant of global concern due to its environmental persistence, bioaccumulation potential, and documented toxicity, carcinogenicity, and mutagenicity. In anaerobic environments, such as contaminated sediments and groundwater, HCH isomers coexist with complex microbial communities, including methanogenic archaea that are crucial for global carbon cycling and ecosystem function. While the biodegradation of HCH by organohalide-respiring bacteria is well-studied, the direct ecotoxicological effects of HCH isomers on methanogens—key indicators of anaerobic ecosystem health—remain poorly understood. Different HCH isomers may exert distinct toxic effects on methanogens, yet the underlying physiological and biochemical inhibitory mechanisms are unclear. This study aims to elucidate the species-specific impact mechanisms of four prevalent HCH isomers (α-, β-, γ-, and δ-HCH) on the physiological metabolism of three representative methanogens with diverse metabolic traits: *Methanobacterium* sp. strain KD21 (a hydrogenotrophic methanogen), *Methanosarcina mazei* WH (a versatile metabolizer), and *Methanospirillum hungatei* (a hydrogenotrophic, spiral-shaped methanogen).

Through a combination of gas chromatography, biochemical assays, and fluorescence-based cellular stress probes, we systematically evaluated methanogenic activity, oxidative stress response, reactive oxygen species (ROS) accumulation, and energy metabolism under HCH isomer exposure. The results revealed profound, isomer- and species-dependent responses. *M. mazei* WH maintained normal methanogenesis under α-, β-, and γ-HCH exposure but was completely inhibited by δ-HCH. In contrast, *M. hungatei* exhibited significantly slowed methane production rates under α- and β-HCH and complete inhibition under γ- and δ-HCH. *Methanobacterium* sp. KD21 demonstrated an intermediate sensitivity profile, with partial inhibition across several isomers, providing a crucial third data point for comparative analysis.

At the mechanistic level, both γ- and δ-HCH triggered significant oxidative stress, activating antioxidant defense systems in all three methanogens. A redox imbalance induced substantial accumulation of intracellular reactive oxygen species (ROS) in *M. hungatei* cells under γ- and δ-HCH stress, severely impairing cellular integrity and function. *M. mazei* WH, however, generated high ROS levels only under the singular stress of δ-HCH, correlating with its complete metabolic inhibition. This elevated ROS interference cascaded into central energy metabolism, significantly affecting membrane-bound ATPase activity and depleting intracellular ATP pools. Detailed ATPase activity kinetics revealed that high ROS levels induced a biphasic response: an initial compensatory increase in enzyme activity, followed by a progressive decline due to oxidative damage. Specifically: (1) δ-HCH induced severe oxidative stress in both *M. mazei* WH and *M. hungatei*, causing a rapid spike in ATPase activity to a peak, followed by an abrupt collapse, ultimately leading to cell inactivation. (2) γ-HCH selectively and gradually reduced ATPase activity in *M. hungatei* without immediate inactivation and had no measurable effect on the enzyme in *M. mazei* WH, underscoring a threshold-based toxicity mechanism.

Thus, methanogen responses to HCH isomers exhibit significant species- and isomer-specific differences, governed by the interplay between the induction of oxidative stress, the capacity of antioxidant defenses, and the sensitivity of core energy-transducing machinery. This study reveals the specific physiological pathways and interspecies mechanistic basis by which HCH isomers inhibit methanogen metabolism. The findings provide critical theoretical insights for more accurately assessing the ecotoxicological risks of HCH in anaerobic environments, predicting the impact of organochlorine pollution on microbial community structure and methane flux, and informing the development of bioremediation strategies in areas where methanogens represent a vital component of the ecosystem.

# Response and functional restructuring of micro-food webs in heavy metal-contaminated soil

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**ABSTRACT**

Heavy metal pollution alters soil organic carbon (SOC) composition by reshaping microbial diversity and interactions. Previous studies mainly focus on the influence of heavy metal pollution on microbial communities at individual trophic level, yet the responses of micro-food webs to heavy metal pollution and their feedback to soil carbon pool remain poorly understood. To address this, we conducted a field survey comprising paired paddy and upland soils along a Cu contamination gradient and explored the contribution of micro-food webs to changes of microbial- and plant-derived carbon in soils. Our results showed that microbial-derived C exhibited greater sensitivity to Cu than plant-derived C, showing rapid accumulation below Cu threshold but declining thereafter. In contrast, plant-derived C showed a consistently increased trend before and post-thresholds. Cu availability, protist-bacterial trophic interactions and viral community were identified as key predictors of soil C components. DNA-SIP further evidenced that protists and viruses involved in the degradation of microbial-derived C. To further investigate the potential of functional restructuring of micro-food webs, we conducted a three-year field experiment and explored the effects of soil amendments on protist-mediated hierarchical interactions and soil ecosystem multifunctionality in heavy metal-contaminated soil. Our results showed that application of soil amendments reshaped protistan community assembly by directly influencing soil pH and Cd availability and indirectly promoting the recovery of bacterial prey. Bacterivorous protists mainly contributed to the dissimilarity of protistan communities between single- and triple-amendments. Furthermore, the restoration of protistan communities facilitated re-establishment of their trophic interactions with bacteria, leading to enhanced microbial network complexity. Our work highlights the importance of micro-food webs in influencing soil carbon dynamics and soil ecosystem functions restoration, with significant implications for remediation assessment and sustainable management of heavy metal-contaminated agricultural soils.

**Keywords:** Micro-food webs; Heavy metal pollution; Soil carbon pool; Trophic interactions

**Acknowledgments**

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# Effects of methane oxidation on microbial mercury methylation in typical paddy soils

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**ABSTRACT**

Microbial methane ($CH_4$) oxidation is a major biological pathway mitigating $CH_4$ emissions in paddy ecosystems. Metabolic intermediates produced during $CH_4$ oxidation may serve as electron donors or carbon sources for mercury (Hg) methylators; however, how $CH_4$ oxidation affects Hg methylation in complex paddy ecosystems remains unclear. Here, we combined $^{13}CH_4$-DNA-stable isotope probing (DNA-SIP) experiments in three typical paddy soils with pure culture assays to investigate the effects of $CH_4$ oxidation on Hg methylation. We found that $CH_4$ addition promoted the production of methylmercury (MeHg) and the expression of Hg methylating genes (Deltaproteobacteria-*hgcA*, Achaea-*hgcA*) in paddy soils. $^{13}CH_4$-DNA-SIP analyses indicated that 62 Hg methylators were significantly enriched in the $^{13}C$-DNA heavy fractions, among which *Anaerolineaceae*, *Geotalea*, and *Veillonellaceae* were significantly enriched in the black, yellow and red soils, respectively. Moreover, pure-culture experiments demonstrated that the addition of methanotrophic metabolites stimulated MeHg production. Combined analyses of $^{13}C$-DNA metagenome-assembly genome and metabolomics revealed that metabolites produced during aerobic $CH_4$ oxidation, such as malate, fumarate and butyrate, played crucial roles in the coupling of aerobic $CH_4$ oxidation and Hg methylation. These findings suggest that the coupling of aerobic $CH_4$ oxidation and Hg methylation in rice field ecosystems is a previously overlooked process, potentially contributing to MeHg production in agroecosystems.

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# Aluminum and microplastic release from reflective agricultural films disrupt microbial communities and functions in soil

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## ABSTRACT

Microplastics are recognized as major global environmental pollutants. Agricultural soils serve as a significant sink for microplastics, with inputs from the degradation of agricultural plastic films. While plastic mulches enhance agricultural productivity, their residual fragments and the microplastics generated pose potential threats. However, the impact of functionally specialized films, such as reflective films widely used in orchards, on soil health remains poorly understood. Reflective films are typically composed of polymers like polyethylene terephthalate (PET) coated with aluminum (Al). We hypothesized that the aging of Al-coated reflective films and the release of Al and microplastics would alter soil pH and micronutrient availability, thereby influencing microbial-mediated carbon (C), nitrogen (N), and phosphorus (P) cycling.

Reflective films were subjected to UVA irradiation, simulated rainfall, and soil burial for up to 120 days. Soil burial induced the most severe and rapid aging. XPS analysis confirmed the oxidation of Al to $Al_2O_3$ on the film surface over time, accompanied by Al shedding. The addition of reflective film-derived microplastics (0.5% w/w) after 120 days of incubation significantly reduced soil pH and available phosphorus (AP), while increasing dissolved organic carbon (DOC) and soil organic carbon (SOC). Notably, the availability of key micronutrients (Fe, Mn, Cu) exhibited a concentration-dependent response: it increased at low film fragment levels but decreased at high microplastic concentrations.

Reflective film amendments altered soil microbial alpha diversity and significantly reshaped community composition. There were a marked enrichment of oligotrophic bacterial taxa and a decrease in copiotrophic bacteria. Fungal communities also changed. Co-occurrence network analysis revealed that reflective films increased network complexity, connectivity, and the proportion of positive interactions among microbes.

The abundance of functional genes involved in C, N, and P cycling responded to film concentration. Low concentrations slightly increased gene abundance, while high microplastic concentrations (0.5%) suppressed most genes. Correlation analyses indicated that the reduced availability of Fe, Mn, and Cu was a key factor negatively correlated with the abundance of these functional genes. In contrast, DOC was negatively correlated with genes for starch hydrolysis and nitrate reduction.

The accelerated aging of reflective films in soil is likely driven by interactions with soil minerals and microorganisms. The concurrent aging releases Al and microplastics. The released Al can lower soil pH, which contributes to decreased micronutrient availability. This creates a nutrient-limited environment that selects for oligotrophic bacteria while disadvantaging copiotrophic bacteria involved in traditional C and N cycling. The suppression of key functional genes, closely tied to micronutrient depletion, suggests a mechanism by which reflective film pollution can hinder soil nutrient cycling efficiency.

This study demonstrates that Al-coated reflective films undergo rapid aging in soil environments, releasing microplastics and Al. These additions alter critical soil properties, reduce the bioavailability of essential micronutrients, and drive microbial communities toward oligotrophic dominance. Crucially, these changes collectively suppress the genetic potential for soil C, N, and P cycling. Our findings reveal that reflective film pollution can indirectly impair soil biogeochemical functions through micronutrient limitation. This underscores the necessity for improved disposal management and long-term field studies.

**Keywords:** Reflective film utilization; Available micronutrients; C, N, P cycling; Functional genes; Microplastics in soil

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# MICROBIAL REFUGEE UNDER SHRUBS LIMITS SOIL COPPER CONTAMINATION EFFECTS

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## ABSTRACT

Copper (Cu) contaminated soils pose a critical environmental challenge by altering soil microbial biodiversity and disrupting essential ecosystem functions. Plants, however, may mitigate Cu impacts on soil microbiomes by buffering free $Cu^{2+}$ activity, recruiting microorganisms, and promoting facilitative interactions. To test these mechanisms, we evaluated Cu bioavailability in field-contaminated soils and assessed whether soil microbiomes respond in ways consistent with the cry-for-help strategy and the stress-gradient hypothesis. The study was conducted in the Puchuncaví Valley (central Chile) across three sites representing uncontaminated, moderately contaminated, and highly contaminated soils. Within each site, two compartments were studied: bulk soil (1 m from vegetation) and soil surrounding roots of the native shrub Baccharis linearis. Atotal of sixty samples were analyzed for chemical properties, including total and soluble Cu concentrations and free $Cu^{2+}$ activity, and regarding their microbiome. Specifically, bacterial and fungal communities were characterized using 16S and ITS amplicon sequencing, with analyses of alpha and beta diversity, co-occurrence networks, and the distribution of generalist, opportunist, and specialist groups. On average, Cu contamination reduced bacterial and fungal richness in bulk soils by 53% and 77%, respectively, while in soil surrounding roots bacterial richness declined by 34% and fungal richness remained unchanged. Compositional divergence between bulk soil and soil surrounding roots increased with contamination, particularly among bacteria: no bacterial families differed between compartments at the uncontaminated site, whereas 15 families differed at the highly contaminated site. Co-occurrence network analyses revealed reduced connectivity in contaminated soils, with greater recruitment of specialist taxa in the rhizosphere and dominance of generalist, parasite-associated fungi in bulk soil. Free $Cu^{2+}$ activity was the strongest predictor of microbial community shifts across compartments and recommended for future monitoring. These findings indicate that Cu contamination severely reshapes soil microbial communities, yet native vegetation can partially buffer these effects by providing microbial refuges consistent with the cry-for-help strategy, while the increase in positive bacterial associations under high Cu a ligns with the stress gradient hypothesis. Together, these results highlight the central role of the rhizosphere in su staining microbial functioning and underscore the need to prioritize plant–microbiome interactions in rest oration planning for contaminated environments.

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# Microbial community assembly and metabolic pathways drive the enrichment of stable DOM under long-term conservation tillage practices in sloping farmlands

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## ABSTRACT

Long-term conservation tillage (CT) practices profoundly influence soil carbon sequestration, yet their molecular-level effects on dissolved organic matter (DOM) stability and associated microbial mechanisms in erosion-prone slopes are poorly characterized. Here, we integrated ultrahigh-resolution mass spectrometry and amplicon sequencing in a typical global erosion zone (red-soil hills, southern China) after 20-year CT practices. Results showed CT practices significantly elevated soil organic matter and transformed DOM composition toward lipid-, protein-, and lignin-like compounds. Microbial diversity substantially increased, with bacterial and fungal genera rising by 23.4%–35.9% and 46.2%–124.4%, respectively. DOM molecular profiles correlated strongly with microbial community assembly and metabolic pathways, particularly aromatic degradation, carbohydrate metabolism, and pentose phosphate pathway. These findings reveal how long-term CT practices—especially contour-tillage combined with straw mulching—enhance DOM stability and soil carbon sequestration via microbial regulation, providing a science-based and transferable strategy for combating land degradation and supporting climate adaptation in vulnerable landscapes worldwide.

**Acknowledgments**

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# Soil metabolic processes influenced by rice roots co-regulates the environmental evolution of antibiotic resistome

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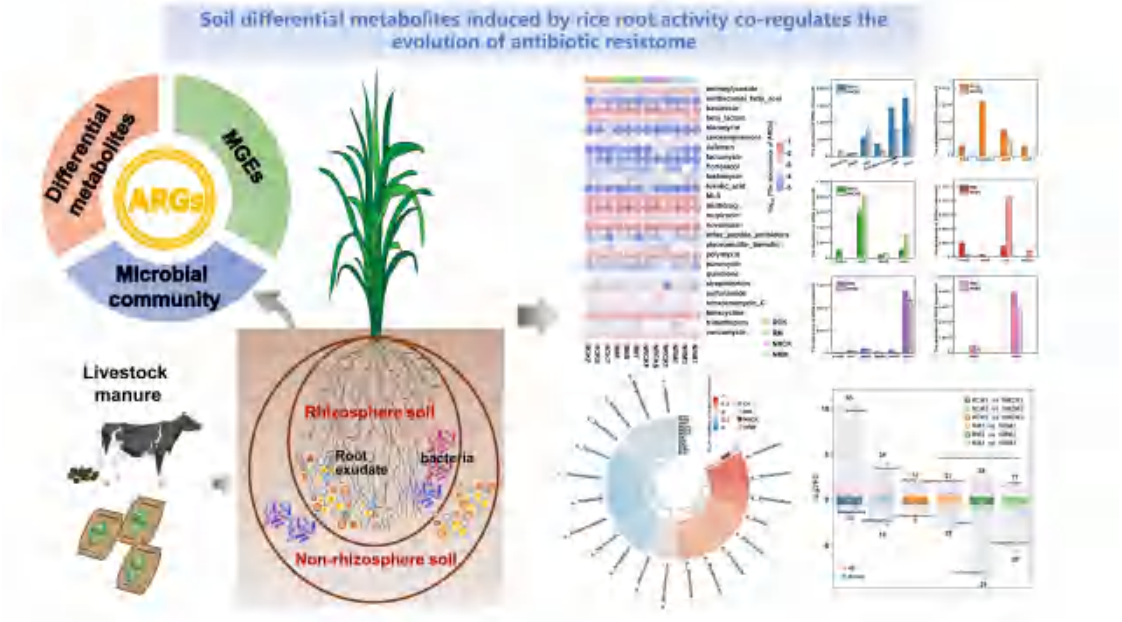
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## ABSTRACT

Plant root activities lead to significant differences in metabolites between the rhizosphere and non-rhizosphere soil, profoundly affecting microbial distribution. However, how this process drives the migration and propagation of manure-derived antibiotic resistance genes (ARGs) in farmland ecosystems remains unclear. Herein, we used a rice pot microcosm experiment to explore the characteristics of antibiotic resistance and bacterial communities in rhizosphere and non-rhizosphere soils and the driving effects of rhizosphere metabolites on ARG propagation. The experiment included no fertilization (CK) and livestock manure application (M) treatments, with samples collected at different rice growth stages. Integrated metagenomic and non-targeted metabolomic analyses were conducted. The results showed significant differences in some ARGs and bacterial diversity in rhizosphere and non-rhizosphere soils, with varied differential ARGs between different growth stages of rice ($P < 0.05$). A total of 496 ARG subtypes and 176 MGE subtypes were identified. Manure application increased the abundance of ARGs, and specific multidrug ARGs (e.g., *mex*C, *acr*F) were significantly enriched in the manure-amended rhizosphere soil. Metabolomic analysis identified 1095 metabolites. Differential metabolites (DEMs) were significantly enriched in distinct pathways: arachidonic acid metabolism in unfertilized soil, and the biosynthesis of secondary metabolites and glutathione metabolism in manure-applied soil. Structural equation modeling (SEM) analysis indicated that ARG distribution differences between rhizosphere and non-rhizosphere soils were mainly regulated by differential metabolites, which influenced the ARG distribution by altering the succession of soil microbial communities and interacting with mobile genetic elements (MGEs). These results demonstrate the role of differential metabolites resulting from rice root activities in co-regulating ARG distribution, providing new insights into the regulatory mechanisms of soil ARG dynamics in paddy fields and highlighting potential strategies to mitigate antibiotic resistance spread.



# Specific metabolites modulate core microbes and microbial interactions to drive fomesafen dissipation in the soybean rhizosphere

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## ABSTRACT

Rhizosphere metabolites mediate organic pollutant dissipation by modulating the rhizosphere microbiome. However, the tripartite mechanistic relationship among metabolite dynamics, microbial community assembly, and pollutant degradation kinetics remains poorly understood. Using an integrated multi-omics approach (16S rRNA amplicon sequencing, untargeted metabolomics, and shotgun metagenomics), this study deciphered the temporal dynamics of rhizosphere metabolites and the microbiome during the dissipation of fomesafen, an herbicide widely used in soybean cultivation, in pot experiments with soybean. Fomesafen dissipation exhibited biphasic kinetics during soybean plant growth, with an initial rapid phase followed by prolonged stabilization, which was synchronized with time-dependent microbiome perturbations of initial enrichment and subsequent attenuation. Metabolomic analysis revealed fomesafen-induced compositional shifts in rhizosphere metabolites, with 2-naphthalenesulfonic acid ( 20.84%) and 2-hydroxyoctadecanoic acid (13.30%) exhibiting opposing regulatory effects on microbial assembly. These metabolites modulated the core microbial assembly and its interactions with potential degraders to ultimately affect fomesafen dissipation. Microcosm experiments confirmed that 2-naphthalenesulfonic acid enhanced while 2-hydroxyoctadecanoic acid inhibited fomesafen dissipation. Our findings highlight the significance of rhizosphere metabolite-mediated interactions between core microbes and potential degraders in driving fomesafen dissipation.

**Acknowledgments**

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# Speciation Distribution, Transformation, and Interfacial Interaction Mechanisms of Heavy Metals and Phosphate in Contaminated Farmland Soils

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**ABSTRACT**

Heavy metal contamination has become a global soil environmental issue. In southern China, agricultural soils are widely affected by heavy metal pollution, predominantly at low to moderate levels. Achieving the safe utilization of moderately and lightly contaminated farmland soils is therefore crucial for ensuring food security. Phosphorus in arable soils is not only an essential nutrient for plant growth but also an inorganic ligand that can significantly influence the mobility, transformation, and fate of heavy metals through synergistic adsorption or site-competition effects.

In recent years, our research group has focused on regionally contaminated agricultural soils in China, conducting systematic investigations into the speciation distribution, transformation characteristics, and interfacial interaction mechanisms of heavy metals and phosphate in soils. Through multiscale studies ranging from the microscopic to the macroscopic level, and by integrating chemical extraction, diffusive gradients in thin films (DGT), statistical correlation analysis, and advanced techniques such as synchrotron-based phosphorus K-edge XANES spectroscopy, in situ infrared spectroscopy, and surface complexation modeling, we comprehensively elucidated the speciation distribution of heavy metals and phosphorus in contaminated farmland soils and their associations with soil reactive mineral. Furthermore, we revealed the effects of phosphate addition on the speciation transformation of iron and heavy metals in flooded soils and clarified the molecular-level mechanisms of co-adsorption between phosphate and typical heavy metal (i.e., Cd) at soil oxide interfaces. These findings provide important scientific evidence and a solid theoretical basis for ecological risk assessment of heavy metals, remediation of contaminated soils, and the safe utilization of agricultural soils.

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# One Health Implications of Treated and Untreated Wastewater Irrigation: Evidence from farmer-managed systems in Northern India

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**ABSTRACT**

The reuse of wastewater for irrigation is expanding rapidly in peri-urban agricultural systems, yet its implications for soil health, groundwater quality, food safety, and farmer livelihoods remain inadequately documented through field-scale evidence. This survey-based study assessed the impacts of wastewater irrigation on soils, groundwater, and agriculture produce under a One Health framework in two major agricultural districts of Punjab, India—Ludhiana and Jalandhar. A total of ten villages (five per district) were selected based on proximity to major wastewater drains, namely Buddha Nullah in Ludhiana and Kala Sanghian Drain in Jalandhar. From each village, 25 composite samples of soil, irrigation water, and crop grains were collected, along with structured farmer perception surveys. Fields irrigated with sewage treatment plant (STP)–treated wastewater, untreated wastewater, and groundwater were comparatively evaluated. Soil quality indicators (pH, electrical conductivity, organic carbon, nutrients, and heavy metals), groundwater parameters, and grain quality were analyzed using standard protocols. Results revealed that irrigation with STP-treated wastewater improved soil nutrient availability and organic carbon status, corroborated by farmer-reported reductions in chemical fertilizer use. However, fields receiving untreated wastewater showed progressive soil quality degradation and significantly elevated concentrations of heavy metals, with chromium emerging as a dominant contaminant across sites. Accumulation of chromium in soils exceeded background levels, raising concerns about long-term soil health, crop safety, and potential groundwater contamination. Farmer perceptions strongly aligned with analytical findings, highlighting both economic benefits and emerging environmental risks. The study underscores that while STP-treated wastewater can enhance soil fertility and reduce fertilizer dependence, inadequate treatment and long-term use of untreated wastewater pose serious threats to soil and human health. Integrating farmer knowledge with soil-based risk assessments is essential to developing safe wastewater reuse strategies within a One Health framework.

**Key Words:** One Health; Punjab; Risk assessment; Soil Health; STP Treated wastewater irrigation

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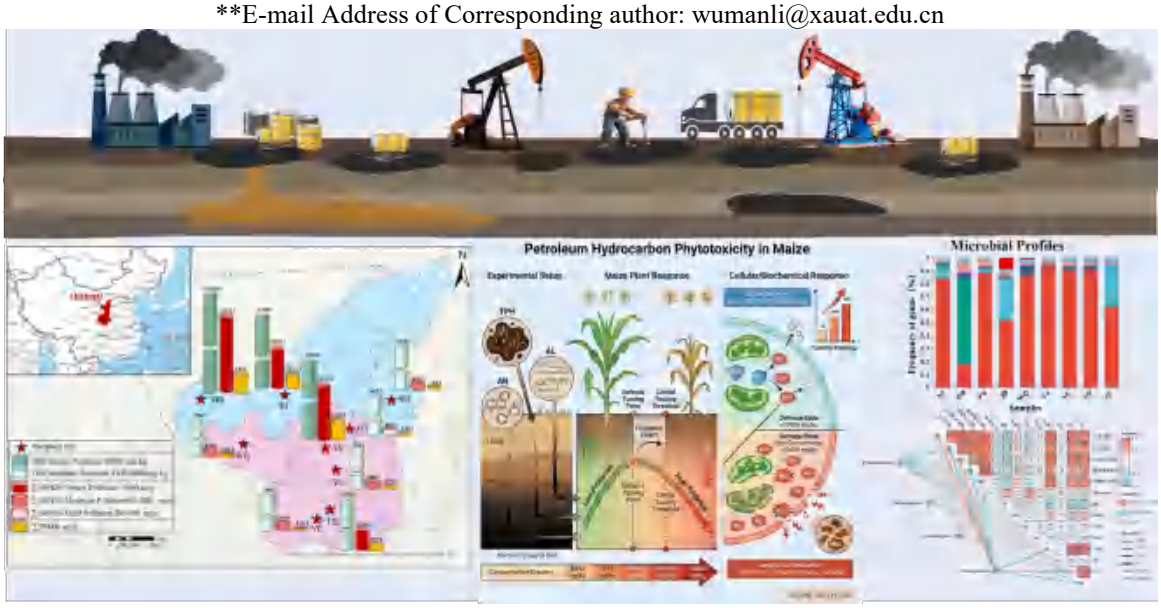
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# Coupling Pollution Screening with Ecotoxicological Response: Critical Thresholds, Aromatic Stress, and Dominant Degraders in the Loess Plateau

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**ABSTRACT**

Soil contamination by toxic xenobiotics from industrial activities is a global challenge. This study investigated biogeochemical processes in the petroleum-rich regions of Northern Shaanxi, China, by integrating pollution screening, phytotoxicity simulations, and analysis of functional microorganisms.

Screening across nine petroleum-contaminated sites revealed significant contamination heterogeneity, with Total Petroleum Hydrocarbon (TPH) concentrations ranging from 4,533 to 146,500 mg·kg$^{-1}$. The concentrations of 16 Polycyclic Aromatic Hydrocarbons (PAHs) ranged from 554.10 to 5,516.73 ng·g$^{-1}$, with carcinogenic PAHs comprising over 30%, indicating substantial ecological risks.

Based on field data, a microcosm experiment using maize (*Zea mays L.*) was conducted to assess ecological impacts within the soil-plant continuum. Three treatment groups-TPH, Aliphatic, and Aromatic hydrocarbons—were applied across a concentration gradient of 5,000-100,000 mg·kg$^{-1}$ for TPH, with equivalent concentrations for other hydrocarbon components. The results revealed a "low-promotion, high-inhibition" hormesis effect, with 10,000 mg·kg$^{-1}$ TPH identified as the threshold for physiological defense activation and 30,000 mg·kg$^{-1}$ TPH as the critical toxicity threshold. Aromatic hydrocarbons exhibited greater phytotoxicity than aliphatic hydrocarbons, significantly inhibiting chlorophyll synthesis and intensifying lipid peroxidation.

Given Aromatic Hydrocarbons as the key toxic factor, microbial responders in contaminated fields were investigated. Bioinformatics analysis of the nine sites PAHs levels was strongly correlated with the *Proteobacteria* phylum. Despite geographical variations, *Pseudomonas sp.* emerged universally as the dominant taxon associated with aromatic hydrocarbon degradation, highlighting its ecological role in mitigating aromatic stress.

In conclusion, this study bridges pollution screening and mechanistic toxicology. By establishing 30,000 mg·kg$^{-1}$ TPH as the toxicity threshold for plants, identifying aromatics as the critical toxic component, and pinpointing *Pseudomonas sp.* as the primary functional degrader, these findings provide a basis for ecological risk assessment and targeted bioremediation strategies in the Loess Plateau.

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# Research on Soil Reconstruction Technology Based on Sand-Clay Compound Ratio in Grassland Open-Pit Mining Areas

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**ABSTRACT**

To address the core ecological reconstruction bottleneck of "water and nutrient deficiency" in the dump sites of typical grassland open-pit mining areas, this study took the dump site of Zhahanaoer Coal Mine as the research object, using local sandy soil and red clay in the mining area as reconstruction substrates. A three-layer structure of "dump subsoil—water-nutrient retention and waterproof layer—clay-sand mixed soil" was constructed, with five clay-sand ratios (1:0, 1:1, 1:2, 1:5, 0:1) and three management measures (fertilization, waterproof layer, and combined fertilization + waterproof layer). The effects of different reconstruction schemes on soil physical and chemical properties, water movement, microbial diversity, enzyme activity, and plant growth were systematically explored, and a comprehensive evaluation was conducted using the entropy-weighted TOPSIS method. The results showed that the medium clay-sand ratios (1:1, 1:2) exhibited a better balance between water retention and nutrient supply. Fertilization significantly improved soil nutrient levels and plant biomass, and the waterproof layer effectively enhanced soil moisture conditions, promoted fungal diversity, and increased some enzyme activities; the combination of the two showed a synergistic effect. Available potassium, urease activity and electrical conductivity were the key indicators distinguishing treatment effects, among which the combination of 1:5 clay-sand ratio + fertilization + waterproof layer achieved the optimal comprehensive restoration effect. The synergistic reconstruction technology of "structural restoration—nutrient supplementation" developed in this study reveals the complex interactions between texture proportioning and management practices within the reconstructed soil system of the dump site. It demonstrates that optimizing suitable sand-clay mixture ratios and management models can significantly improve soil moisture, nutrient availability, and microbial functionality, thereby enhancing vegetation growth and carbon sequestration potential. This provides a scientific basis and scalable engineering solution for the rapid vegetation restoration of dump sites in typical grassland open-pit mining areas, holding important theoretical and practical significance for promoting the construction of green mines.

**Key words:** grassland open-pit mining areas; ecological reconstruction; sand-clay ratio optimization soil; plant effects

# Genotypic Variability in Bioaccumulation and Dietary Risks of PFAS across 30 Wheat Cultivars: A Field Assessment

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**ABSTRACT**

Soil contamination by per- and polyfluoroalkyl substances (PFAS) in agricultural ecosystems poses a significant threat to global food security. While soil-to-plant transfer is a recognized pathway, the influence of crop genetic factors remains poorly integrated into risk assessment frameworks. In this study, the occurrence, bioaccumulation, and genotypic variability of $\Sigma_{25}$PFAS were systematically investigated across 30 wheat cultivars. These cultivars were grown under identical field conditions in a region affected by industrial activities involving fluorochemicals. Grain samples were collected at the stage of maturity. PFAS concentrations were quantified using high-performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS). A striking 3-fold heterogeneity in total grain PFAS concentrations was observed among the 30 genotypes. Genetic diversity was identified as a primary driver of PFAS accumulation in wheat grains. Among $\Sigma_{25}$PFAS, short-chain perfluoroalkyl carboxylic acids (PFCAs) showed significantly higher soil-to-grain transfer efficiencies compared to long-chain congeners. Four dominant species (PFBA, PFPeA, PFHxA, and PFOA) accounted for the majority of the total PFAS burden. Different partitioning patterns of four dominant analogs were exhibited within the grains, even under identical soil concentrations. Moreover, plant height was found to facilitate the accumulation of PFAS, particularly PFPeA and PFHxA, in wheat grains. Furthermore, the estimated daily intake (EDI) and hazard quotients (HQ) derived from grain consumption were calculated for 30 cultivars. A threefold difference in HQ estimations was observed between high- and low-accumulating genotypes. It is suggested that neglecting inter-cultivar variability may lead to substantial uncertainties in regional dietary risks. The potential misclassification of exposure risks for local populations was also highlighted. These findings underscore the importance of integrating genetic heterogeneity into environmental regulatory frameworks. The results suggest that leveraging low-accumulation cultivars offers a cost-effective and sustainable strategy to mitigate PFAS transfer into the human food chain. Regional food security in contaminated agricultural ecosystems could be ensured through targeted cultivar selection.

# Comparative Study on the Efficiency of Multiphase Extraction Combined with Bioremediation and Thermal Enhanced Coupling Process

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## ABSTRACT

Petroleum hydrocarbon contamination in soil and groundwater of decommissioned petrochemical sites causes long-term adverse effects and prominent eco-environmental risks. Multiphase extraction coupled with bioremediation has become the core in-situ remediation technology for such contaminated sites. To explore the strengthening mechanism and application advantages of temperature regulation on remediation performance, two comparative experiments were conducted in this study, namely conventional multiphase extraction- biostimulation (MPE-BS) and thermally enhanced multiphase extraction-biostimulation (MPE-HEBS). The dynamic variations of soil temperature, microbial abundance, microbial metabolic activity, and volatile organic compound (VOCs) concentration in extracted gas were systematically monitored. The removal characteristics of total petroleum hydrocarbons (TPH) in the fractions of $C_6$–$C_9$ and $C_{10}$–$C_{40}$ in soil and groundwater were quantitatively analyzed, and a comprehensive evaluation was performed combined with significant difference analysis.

The results showed that both processes could effectively reduce petroleum hydrocarbon pollutants, and there were significant differences in remediation effects between the two groups ($P < 0.05$). The MPE-HEBS process could stably increase in-situ soil temperature and break the restriction of low-temperature environments. Compared with MPE-BS, MPE-HEBS possessed higher microbial abundance and stronger carbon dioxide metabolic activity in soil gas, as well as more stable proliferation of indigenous degrading microorganisms. The relative abundance of *Pseudomonas* and *Thermicanus* increased significantly. Meanwhile, thermal enhancement elevated the peak concentration of VOCs and advanced the peak time, which greatly accelerated the desorption, volatilization and removal of pollutants. In the middle remediation stage, the removal rates of petroleum hydrocarbons with different carbon chain fractions in the MPE-HEBS group were 15.3%–28.5% higher than those in the MPE-BS group. At the end of remediation, lower residual pollutant concentration and better overall removal performance were achieved in the MPE-HEBS group. This study can provide theoretical basis and technical References for the efficient in-situ remediation of petroleum hydrocarbon-contaminated sites in decommissioned petrochemical and refining areas.

# More Than Containment: An Innovative Attempt to Solve Groundwater Contamination at Landfills —— The Application of a Nation's First Full-Process Technical System Integrating Source, Pathway, and End-of-Pipe Treatment

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**ABSTRACT**

Globally, landfilling remains one of the primary methods for municipal solid waste disposal. However, significant differences exist among countries in the level of pollution control at landfill sites. Due to China's large population base, high waste generation, and a lengthy history of resource recovery efforts, there remains substantial numbers of legacy landfill sites in China, with municipal solid waste landfills accounting for a high proportion. As a result, various environmental problems have been continuously exposed, with groundwater pollution caused by leachate leakage being particularly prominent. This has become a key bottleneck threatening the safety of China's groundwater resources and constraining high-quality ecological development. Currently, a singular "containment-oriented" model is generally adopted for groundwater contamination control at Chinese landfill sites, focusing primarily on the physical blocking of leachate migration pathways. While this model can, to some extent, prevent further contaminant migration, it cannot reduce leachate generation at the source, nor can it effectively remediate already contaminated groundwater. Thus, there is an urgent need to break through traditional thinking and construct comprehensive and systematic technical system. To address this need, this study takes a comprehensive remediation project at an actual municipal solid waste landfill site (focusing on groundwater contamination) as its research vehicle, conducting a national-first attempt to apply a full-process technical system integrating "source– pathway – end-of-pipe treatment." Based on multi-source data fusion, the study achieved precise identification of pollution sources, dynamic monitoring of contaminant plumes, as well as calibration and simulation of the target landfill. On this basis, multidimensional technologies including source reduction, pathway interception, pollution remediation, and dynamic tracking were further coupled, forming a closed-loop control mechanism based on "monitoring-feedback-regulation" of groundwater quality. This study aims to overcome the traditional limitations of "only blocking without treating, and only treating without preventing," systematically solving the problem of groundwater contamination at landfills, and providing a technical References and practical demonstration for similar projects in China.

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# Earthworms and Crop Varieties Mediate the Effects of Nano-Hydroxyapatite on Soil Biochemical Characteristics and Cadmium Uptake by Plant

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## ABSTRACT

Using nano-hydroxyapatite (nHAP) to immobilize cadmium (Cd) is a promising approach for soil remediation. However, biotic factors, such as earthworms, might affect its effectiveness by altering soil biochemistry and the Cd cycling process. Nonetheless, the relative contributions of crop types and their varieties, along with earthworms, in nHAP-mediated Cd remediation remain poorly understood. A field experiment was conducted to evaluate the effects of nHAP, earthworms, and their combination on soil biochemical characteristics and Cd accumulation across different crop types and varieties. The experiment consisted of 20 treatments, each with a plot size of 4.5 m² and three replicates. The treatments applied 15kg·ha$^{-1}$ nHAP and 11 worms·m$^{-2}$. Cd uptake was measured in two corn (*Zea mays*) varieties - Jin Zhongyu (YD) and Yue Sweet-9 (YG), as well as in two leafy vegetables (*Brassica campestris*) varieties Guang Fu-35 (DG) and Bi Qingtian (DD). Soil biochemical properties and Cd speciation were analyzed in non-plant soil, bulk soil, and rhizosphere soils. Our findings indicated the distribution of Cd fractions in rhizosphere soil varied between leaf vegetables and corn: higher contents of bioavailable Cd (exchangeable and water soluble) were observed in the DD treatment compared to others, while stable Cd forms (residual and oxidizable) were more prevalent in the YG treatment. Total microbial biomass was lowest in non-planted soil and highest in leafy vegetable soil, especially in the DD under the nHAP-earthworm co-application. nHAP increased soil microbial biomass more effectively in corn treatment, whereas earthworms shifted the microbial community toward greater dominance of Gram-positive bacteria ($G^+$) and fungi. Bacterial dominance in soil remained consistently higher in leafy vegetable treatment across all amendment treatments. The DD vegetable variety absorbs up to 35% more Cd than the corn varieties, with higher bioaccumulation in the edible tissues. The amendments had opposing effects on Cd uptake by plant: nHAP decreased Cd accumulation, while earthworms increased it. Crucially, their combined effect significantly increased Cd accumulation in the leafy vegetable but reduced it in the corn, particularly in the YD variety, revealing crop-variety-specific responses in Cd uptake patterns. Principal component analysis (PCA) indicated that low Cd uptake was linked with elevated pH, higher exchangeable Ca and increased urease activity, a predominance of Gram-negative ($G^-$) bacteria, and a shift of Cd toward stable forms (oxidizable and residual). Conversely, increased Cd uptake was correlated with increased $G^+$ bacteria, fungi biomass, and invertase activity, enlarging pools of exchangeable and water-soluble Cd. This study provides critical insights into predicting Cd transfer into the food chain, demonstrating that effective remediation strategies must account for specific crop types and soil biochemical activity.

Keywords: Earthworm, Crop variety, Microbial characteristics, Nano-hydroxyapatite, Cd accumulation

# Remediation of Cadmium-Contaminated Soil via the Coupling of Marigold-Water Spinach Intercropping and Passivation

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**ABSTRACT**

Background and aim: High-accumulation plants intercropped with economic crops, coupled with passivators, represent a novel approach for remediating cadmium (Cd)-contaminated soil. Methods: We employed a pot experiment to investigate the effects of intercropping coupled with passivation on plant growth, Cd accumulation, and soil Cd content. Results: The results demonstrated that intercropping marigold (*Tagetes erecta L.*) with water spinach (*Ipomoea aquatica*), coupled with passivation treatment, reduced the content of bioavailable and total Cd in soil by 45.07–48.78% and 13.12–17.95%, respectively. This approach promoted the transformation of Cd from weakly acidic and reducible forms to oxidizable and residual forms, with the proportion of residual Cd being significantly higher than that in treatments involving intercropping alone or application of passivators only. The combined intercropping and passivation treatment significantly enhanced Cd accumulation in both marigold and water spinach by 4.80–25.53% and 106.44–134.90%, respectively, compared with that of intercropping-only and passivation-only treatments. Furthermore, this integrated approach reduced heavy metal concentration in edible parts of water spinach, while significantly increasing Cd accumulation in its below-ground biomass. Conclusions: These findings highlight the potential of integrating intercropping with passivation for remediation of Cd-contaminated soil, particularly demonstrating that the marigold-water spinach intercropping system serves as an effective strategy for mitigating Cd pollution in soils.

# Root acid phosphatases and microbial biomass phosphorus induced Cd tolerance and P acquisition in wheat inoculated with P solubilizing bacteria.

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**ABSTRACT**

Microbial bioremediation has emerged promisingly to improve crop tolerance to cadmium (Cd). Moreover, Cd tolerance and phosphate acquisition in plants positively correlated under P solubilizing bacteria inoculation, yet there is no evidence on specific mechanisms influencing Cd tolerance and plant P acquisition. The present study evaluates Cd tolerance in rock P-amended durum wheat in response to inoculation with P solubilizing bacteria (PSB) [three individual isolates *Bacillus siamensis*, *Rahnella aceris*, *Bacillus cereus* and their consortium ($PSB_{Cs}$)] and consequently reveals key rhizosphere mechanisms involved in both Cd tolerance and P use efficiency. Results show that overall inoculation improved plant growth, rhizosphere parameters and nutrient uptake (P, N, K) under increasing Cd concentrations [8 ($Cd_8$) and 16 ($Cd_{16}$) ppm $Cd^{2+}$]. Under $Cd_{16}$, *Rahnella aceris* induced the most significant plant responses in terms of biomass [shoots (31%), roots (40%), and spikes (92%)], rhizosphere available P (234%) and root inorganic P (109%) compared to uninoculated plant. Microbial biomass P (MBP) and root acid phosphatases (APase) were 33-and 13-times higher, respectively, than in uninoculated plants. In addition, inoculation (particularly using $PSB_{Cs}$) significantly decreased Cd translocation factor (TF) ($Cd_8$: −17% and $Cd_{16}$: −22%) and Cd bioaccumulation factor (BAF) ($Cd_8$: −6% and $Cd_{16}$: −40%) concomitantly to enhanced root morphological traits and P contents in shoots and spikes. Furthermore, PSB inoculation under Cd constraint increased (rhizosphere available P/MBP) and (root APase/rhizosphere APase) ratios that significantly ($p<0.05$) correlate with plant P uptake in shoots and spikes. Increase in both ratios was concomitant to a significant decrease in TF and BAF of Cd exemplified by negatively significant correlations ($r^2=0.70$ and $r^2=0.57$, $p<0.05$). This finding elucidates the key role of bacterial inoculation that presumably triggered Cd tolerance and aboveground P owing to increased (rhizosphere available P/MBP) and (root/rhizosphere APase) ratios in PSB-inoculated wheat.

**Keywords:** Cadmium-tolerance, phosphorus, P uptake, rhizosphere, translocation factor.

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Mohammed VI Polytechnic University

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# Nitrogen Transfer and Cross-feeding Between Azotobacter chroococcum and Paracoccus aminovorans Promotes Pyrene Degradation

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**ABSTRACT**

Nitrogen is a limiting nutrient for degraders function in hydrocarbon-contaminated environments. Biological nitrogen fixation by diazotrophs is a natural solution for supplying bioavailable nitrogen. Here, we determined whether the diazotroph *Azotobacter chroococcum* HN can provide nitrogen to the polycyclic aromatic hydrocarbon-degrading bacterium *Paracoccus aminovorans* HPD-2 and further explored the synergistic interactions that facilitate pyrene degradation in nitrogen-deprived environments. We found that *A. chroococcum* HN and *P. aminovorans* HPD-2 grew and degraded pyrene more quickly in co-culture than in monoculture. Surface-enhanced Raman spectroscopy combined with $^{15}N$ stable isotope probing (SERS-$^{15}N$ SIP) demonstrated that *A. chroococcum* HN provided nitrogen to *P. aminovorans* HPD-2. Metabolite analysis and feeding experiments confirmed that cross-feeding occurred between *A. chroococcum* HN and *P. aminovorans* HPD-2 during pyrene degradation. Transcriptomic and metabolomic analyses further revealed that co-culture significantly upregulated key pathways such as nitrogen fixation, aromatic compound degradation, protein export, and the TCA cycle in *A. chroococcum* HN and quorum sensing, aromatic compound degradation and ABC transporters in *P. aminovorans* HPD-2. Phenotypic and fluorescence in situ hybridization (FISH) assays demonstrated that *A. chroococcum* HN produced large amounts of biofilm and was located at the bottom of the biofilm in co-culture, whereas *P. aminovorans* HPD-2 attached to the surface layer and formed a bridge-like structure with *A. chroococcum* HN. This study demonstrates that distinct syntrophic interactions occur between *A. chroococcum* HN and *P. aminovorans* HPD-2 and provides support for their combined use in organic pollutant degradation in nitrogen-deprived environments.

**Keywords:** Polycyclic aromatic hydrocarbons, Synthetic microbial communities, Biodegradation, Diazotrophs, Degrading bacterium

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# Biohydrogen Utilization in Legume-rhizobium Symbiosis Reveals a Novel Mechanism of Accelerated Tetrachlorobiphenyl Transformation

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**ABSTRACT**

Molecular hydrogen ($H_2$) is an important green energy source and plays vital roles in environmental remediation. Legume-rhizobium symbioses are not only a major producer of $H_2$ in terrestrial ecosystems but also an important resource for the *in situ* biodegradation of environmental pollutants. However, the role of $H_2$ in pollutant biotransformation by symbiotic associations is unknown. Here, symbiosis between *Glycine max* and *Bradyrhizobium diazoefficiens* were used as a model system to investigate whether biohydrogen utilization promotes the transformation of the tetrachlorobiphenyl PCB77. Both a $H_2$ uptake-positive ($Hup^+$) strain (wild type) and a $Hup^-$ strain (a *hupL* deletion mutant) were inoculated into soybean nodules. Compared with $Hup^-$ nodules, $Hup^+$ nodules increased dechlorination significantly by 61.1% and reduced the accumulation of PCB77 in nodules by 37.7% ($p < 0.05$). After exposure to nickel, an enhancer of uptake hydrogenase, dechlorination increased significantly by 2.2-fold, and the accumulation of PCB77 in nodules decreased by 54.4% ($p < 0.05$). Furthermore, the tetrachlorobiphenyl transformation in the soybean root nodules was mainly testified to be mediated by nitrate reductase (encoded by the gene *NR*) for tetrachlorobiphenyl dechlorination and biphenyl-2,3-diol 1,2-dioxygenase (*bphC*) for biphenyl degradation. This study demonstrates for the first time that biohydrogen utilization has a beneficial effect on tetrachlorobiphenyl biotransformation in a legume-rhizobium symbiosis. In a broader view, this work highlight the previously unrecognized but important role of biohydrogen uptake in the phytoremediation of halogenated organic compounds.

**Keywords:** Legume-rhizobium symbiosis, biohydrogen, soil, polychlorinated biphenyls, biodegradation

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# Variations in root functional traits facilitate the adaptation of pioneer plants to rare earth element mine tailings

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**ABSTRACT**

To satisfy the growing global demand for rare earth elements (REEs)—key components in high-tech products and low-carbon technologies—mining activities have resulted in numerous anthropogenically degraded tailings, causing large areas characterized by soil degradation, vegetation loss, and biodiversity decline. These tailings exhibit REEs contamination, nutrient deficiency, and soil compaction. Even after a decade of abandonment, only a few pioneer plant species—mainly the grass species *Miscanthus sinensis* Anderss., the fern species *Dicranopteris linearis* (Burm. f.) Underw., and the tree species *Pinus massoniana* Lamb.—have managed to establish sparse populations in REEs mine tailings. But the mechanisms enabling these pioneer species to survive in stress tailings remain poorly understood.

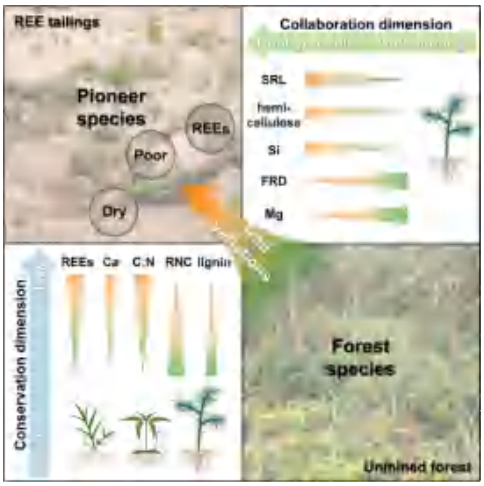
The trade-offs in plant root traits significantly influence the adaptation and community dynamics in heterogeneous habitats. However, the role of inter- and intraspecific root trait variation in the adaptation of pioneer plants in stressed tailings remains limited. A clear understanding of root trait strategies is essential for guiding ecological restoration with nature-based solutions in severely degraded mining landscapes.

In this study, we assessed root morphological and chemical traits of 16 dominant species from unexploited forest sites adjacent to rare earth elements (REEs) mine tailings, and three pioneer species (*M. sinensis, D. linearis, P. massoniana*) across a gradient of soil stress—including REEs toxicity, nutrient deficiency, and compaction—from forest to REEs tailings.

In the two-dimensional root economics space (RES), the contents of cellulose, hemicellulose, and silicon were coaxial with the collaboration gradients ("do-it-yourself"–"outsourcing") and inversely related to fine root diameter. Meanwhile, root REEs content aligned with conservation gradients ("fast"–"slow"), indicating a slow strategy.

Interspecific variations did not show a distinct strategy pReferences for pioneer species compared to non-pioneer plants. However, notable intraspecific variations were observed, particularly in stress-related traits such as root N content, C:N ratio and REEs content, which exceeded interspecific variations. All three pioneer species exhibited a shift toward "slow" strategies, while *P. massoniana* also transitioned toward "do-it-yourself" strategies, driven by increased soil bulk density, elevated bioavailable REEs content, and reduced soil carbon and nutrient levels in the tailings.

Synthesis and applications: Our findings highlight the pivotal role of root chemical traits and intraspecific plasticity in facilitating the adaptation of pioneer plants to extreme REE tailing environments, particularly the capacity of shifting toward conservative ("slow") strategies and self-reliant ("do-it-yourself") nutrient acquisition under stress. This provides practical guidance for selecting suitable pioneer species in the phytoremediation of REE-contaminated tailings, where high phenotypic adaptability may be critical for establishment and survival.




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# Phytoremediation of heavy metals in soils of the Christchurch Red Zone

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**ABSTRACT**

Worldwide, coastal cities are planning the retreat from low-lying areas due to climate change, where heavy metal contamination is common. In Christchurch, New Zealand, some 600 ha of the city became unusable following the Canterbury Earthquake Sequence (CES) in 2010-11. Soils in the "Red Zone" (RZ) contain Pb, Cu, and Zn derived from historic construction materials, coal-tar residues, and stormwater inputs. As these contaminants are typical of urban residential soils worldwide, the RZ profile represents the kinds of contaminated soils expected in managed retreat. As large-scale excavation or capping is impractical, phytoremediation offers a feasible, nature-based solution, but evidence is limited for New Zealand conditions, particularly regarding local plant species and amendment-enhanced stabilisation. One contamination hotspot contained up to 22,000 mg $kg^{-1}$ Cu, 13,000 mg $kg^{-1}$ Zn, and over 1,000 mg $kg^{-1}$ Pb. Toxicity tests carried out in the greenhouse with this RZ soil blended with non-contaminated soil showed that the lowest concentration that produced a significant effect of biomass on Lolium perenne was 100% RZ soil. This concentration decreased to 12.5% on Phaseolus vulgaris. L. perenne still grew at 100% RZ, whereas P. vulgaris showed clear symptoms of stress.

Lysimeter trials (2.3 L; 100% RZ soil) quantified how seven organic amendment treatments influence metal leaching and plant performance. Treatments included two pine biochars, compost, two biochar – compost mixtures, a biosolids – sawdust blend, and an unamended control. Amendments were applied at ~4% of soil dry mass (equivalent to ~60 t $ha^{-1}$). One type of biochar – compost treatment most effectively reduced Cu, Zn, and Pb mobility while promoting healthy ryegrass growth, demonstrating synergistic benefits for both immobilisation and plant establishment. Biosolids and Biochar-I treatment increased Zn leaching compared to unamended control, and Biochar-I treatment increased Cu/Pd leaching compared with unamended control.

This integrated greenhouse – lysimeter – field framework identifies which organic amendments — such as biochar, compost, and biosolids—and which plant species can effectively stabilise metals under real conditions, providing practical guidance for restoring contaminated residential land undergoing managed retreat.

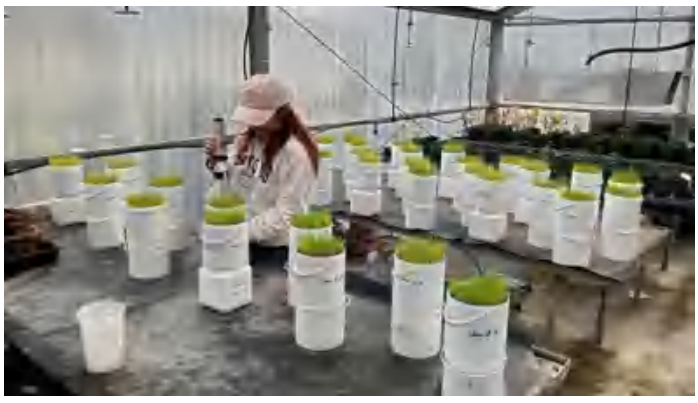


Fig.1: Lysimeter experiment in greenhouse.

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Christchurch City Council

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Phytoremediation of heavy metals in soils of the Christchurch Red Zone

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# Transforming Spent Coffee Grounds (SCG) into an Environmental Asset- Its Characterization and Optimization for Soil Amendment and Remediation Applications

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**ABSTRACT**

Global coffee consumption continues to escalate rapidly, significantly increasing spent coffee grounds (SCG) produced. An estimated 18 million wet tonnes were produced worldwide in 2021 (Kim et al., 2024). SCG are an abundant organic waste stream with potential for soil remediation; however, their direct application, without processing, can cause more problems. This study investigates the potential of SCG and SCG-derived biochar as amendments to soil for immobilizing heavy metals in contaminated urban soils.

The SCG were oven-dried at 40°C for 48-hours. Half the grounds were stored, and the other half were pyrolyzed at 550°C. Six small batches resulted in average yields between 20.5 and 23.3%. These were then modified with $H_2O_2$ solution (30%) at a rate of 1: 20w/v. The resultant substrates were analysed before use in a soil column experiment.

The analyses show that pyrolysis increased pH in the pristine biochar, as expected, while those modified with $H_2O_2$ decreased in pH both SCG and biochar. BET (Brunauer-Emmett-Teller) analysis revealed an average of an approx. 40% increase in surface area due to pyrolysis. Modification of SCG resulted in a 6% reduction in surface area, while biochar modification resulted in a 14% increase in surface area. FTIR and NMR analyses showed that SCG contains some oxygen-containing functional groups, such as carboxyl (COOH), hydroxyl (-OH), carbonyl (C=O), and phenolic groups, which are essential for pollutant remediation. Modification with $H_2O_2$ enhanced these, especially on the biochar, where they had been lost through pyrolysis. Conversion of SCG to biochar also increased thermal stability, which has implications for carbon sequestration and long-term environmental stability. These findings suggest that SCG-derived materials offer a promising, circular economic approach to urban soil remediation, converting coffee waste into valuable environmental remediation agents while reducing heavy metal mobility. Next steps in this research will analyse the efficacy of these on heavy metal-contaminated soils.

**Keywords:** SCG, biochar, heavy metals, remediation, carbon sequestration.

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# Differential responses of phoC- and phoD-harbouring bacterial communities to cadmium stress and microbial inoculation in a rapeseed pot system

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**ABSTRACT**

Cadmium (Cd) contamination is a pervasive constraint in agricultural soils, impairing crop growth and disrupting nutrient cycling, particularly phosphorus (P) transformation. Microbial P mineralization is largely mediated by phosphatase-producing bacteria carrying phoC and phoD, yet how these two functional guilds jointly and differentially respond to Cd stress remains poorly understood.

To address this gap, we conducted a pot experiment with four treatments (control, inoculation with microbial solution, cadmium addition, and inoculation with cadmium) to evaluate how cadmium pollution and microbial inoculation reshape soil phosphorus cycling microbes and their functional capabilities. We found that cadmium stress significantly altered soil properties and phosphatase activity, reshaping the communities of phoC and phoD. The response of phoC bacteria to inoculation was particularly strong, exhibiting greater tolerance to Cd and a higher tendency to be activated by inoculation, thus promoting soil remediation. In contrast, phoD showed a greater loss of diversity and was more sensitive to Cd and pH, with a narrower ecological niche indicating limited recovery potential. Functional gene predictions based on amplicon sequencing results revealed significant differences among three important functional modules: cadmium addition inhibited the phosphorus cycling and heavy metal stress response modules, while microbial inoculation selectively restored the enzyme-related phosphatase module in contaminated soils. Correlation analysis and SEM jointly indicated that P enzyme-related functional genes are a crucial microbial functional pathway directly regulating plant cadmium accumulation, rather than P cycling functional genes or heavy metal stress response genes.

Our results demonstrate that phoC and phoD communities exhibit both shared and contrasting ecological responses to Cd × inoculation, and that their functional divergence governs P-cycling potential under heavy-metal stress. By identifying the P_enzyme module as the key microbial–plant interface, this study provides mechanistic insight and a clear functional target for developing microbe-assisted strategies to mitigate Cd risks in contaminated farmland.

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# Metabolic complementary Between Cupriavidus and Pseudomonas Facilitates 2,4,6-Trichlorophenol Degradation

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**ABSTRACT**

Halogenated aromatic compounds with high degrees of chlorine substitution are generally recalcitrant to direct oxidative biodegradation due to their high redox potentials (Hug et al., 2013). Among them, 2,4,6-trichlorophenol (TCP) is widely used in paper bleaching, dyes, pesticides, and pharmaceuticals. Owing to its persistence, carcinogenicity, and ecological toxicity, TCP has been classified as a priority environmental pollutant. Industrial effluents contain TCP reaching several hundred mg/L, far exceeding the World Health Organization guideline of 200 μg/L for drinking water. Consequently, bioremediation of TCP often relies on anaerobic reductive dechlorination followed by aerobic oxidation (Ghochlavi et al., 2022). However, complete reductive dechlorination is rarely achieved by organohalide-respiring bacteria, leading to the accumulation of partially dechlorinated and still-toxic intermediates. Only *Cupriavidus necator* spp. have been reported to mineralize and degrade TCP completely in aerobic condition (Lykidis et al., 2010, Sánchez and González, 2007).

In this study, we identified an efficient aerobic TCP-degrading microbial consortium composed of *Cupriavidus* sp. and *Pseudomona*s sp., capable of completely removing up to 450 mg/L TCP using TCP as the sole carbon and energy source. Metagenomic analysis revealed that *Cupriavidus* encoded a complete TCP catabolic pathway, while *Pseudomonas*, though unable to degrade TCP independently, harbored genes for downstream intermediate processing and likely benefited from metabolites released by *Cupriavidus*. Co-culture experiments confirmed enhanced degradation efficiency compared to *Cupriavidus* monocultures, indicating a metabolically complementary interaction.

These findings highlight the potential of cooperative microbial metabolism in facilitating high-concentration TCP mineralization and provide insight into functional division of labor during the biodegradation of recalcitrant halogenated pollutants.

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# Root foraging for metals as a key trait of hyperaccumulators may be obscured in soil systems: Evidence from experiments and a meta-analysis

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**ABSTRACT**

Root foraging for metals is increasingly recognized as a distinctive trait of hyperaccumulator species, yet its occurrence varies widely among species, elements, and experimental conditions. Here, we sought to clarify (i) the factors that influence the detectability of metal-directed root foraging and (ii) the functional advantages this trait provides. We combined split-root experiments in hydroponic and soil systems using hyperaccumulating (HE) and non-hyperaccumulating (NHE) ecotypes of *Sedum alfredii* together with a meta-analysis of published datasets on hyperaccumulators root responses to heterogeneous metal distribution. The HE exhibited a rapid and consistent foraging response in hydroponics, allocating 62.1% of its root biomass to the Cd-enriched compartment within 5 days and maintaining a similar allocation (62.2%) after 21 days. In contrast, this response was not detectable in sticky paddy soil, where the HE allocated only 47.3% of its root biomass to the Cd-rich side over 70 days. The NHE showed stable avoidance of Cd-rich patches in both cultivation systems. Meta-analysis revealed that, beyond plant traits, soil texture, soil source, and the origin of metal heterogeneity were the dominant determinants of whether foraging behavior could be observed. The contrasting ecotypic responses indicate that Cd foraging is a characteristic trait associated with hyperaccumulation: the HE predominantly translocated Cd to shoots, whereas the NHE retained most Cd in roots. Across studies, positive root responses to metal-rich patches increased local morphological investment and were positively correlated with whole-plant biomass and metal uptake. Together, our findings demonstrate that soil environments especially soil texture can obscure the intrinsic foraging capacity of hyperaccumulators, and that metal-directed root foraging is an adaptive trait tightly linked to growth maintenance and metal hyperaccumulation.

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# Sulfate-Amended In Situ Bioremediation of Chloroethene-Heavy Metal Co-Contamination: Mechanisms, Microbial Responses, and Pilot-Scale Validation

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## ABSTRACT

Chloroethenes and heavy metal(loid)s (HMs) frequently co-occur in industrially contaminated groundwater, posing serious risks to ecosystems and human health. While in-situ bioremediation is an effective approach for treating chlorinated ethenes such as tetrachloroethene (PCE) and trichloroethene (TCE), its performance is often limited by the inhibitory influence of coexisting HMs, resulting in the accumulation of toxic intermediates such as dichloroethene (DCE) and vinyl chloride (VC). Despite extensive studies on the dechlorination of parent compounds, the relationships between low-chlorinated product kinetics and HM exposure levels remain poorly understood, as do the mechanisms of HM-induced inhibition on microbial reductive dechlorination.

In our study, arsenic and chromium were selected as representative HMs to systematically elucidate the differential inhibitory mechanisms and microbial community responses under combined chloroethene-HM stress, focusing on dechlorination kinetics, electron-donor availability, and core functional microorganisms. Leveraging the natural coexistence of sulfate-reducing bacteria (SRB) and organohalide-respiring bacteria (OHRB), we further proposed a sulfate-amendment strategy for the synergistic remediation of chloroethene-HM composite pollution. By optimizing sulfate input (50–75 μM) according to the type and concentration of coexisting metals, the strategy significantly enhanced reductive dechlorination efficiency under various HM exposures. Concurrently, SRB-mediated sulfide generation promoted metal sulfide precipitation, achieving over 95% removal of 50 μM As(III), Ni(II), Pb(II), and Cu(II), thereby realizing simultaneous detoxification and pollutant degradation. Eventually, the integration of our strategy with electrokinetic bioremediation (EK-BIO) was validated in laboratory and pilot-scale experiments. The 98-day EK-BIO pilot test achieved over 90.0% TCE removal and a 74.0% chloroethene-to-ethylene conversion efficiency, providing both mechanistic insight and practical guidance for the in-situ remediation of chloroethene-HM co-contaminated sites.

**Keywords:** Chloroethenes, Microbial dechlorination, In-situ bioremediation, Heavy metal.

**Acknowledgments**

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# Phytomining of rare earth elements from phosphogypsum waste heaps using silver birch (Betula Pendula Roth)

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**ABSTRACT**

Rare earth elements (REEs) are critical inputs to many clean technology applications. Phosphogypsum, which is a waste generated during phosphorus fertilizer production, is identified as a promising secondary source of these elements. However, the behaviour of REEs in this material and their transfer to trees remains poorly understood. Therefore, the study aimed to assess REE contents in technogenic soils formed on phosphogypsum waste dumps and to evaluate the potential use of silver birch (*Betula pendula* Roth) in the REE phytomining process. The investigation was conducted on two heaps in Łąka village (southern Poland) and Wiślinka village (northern Poland). Fieldwork comprised sampling of biomass (leaves and fine roots) from mid-sized birches, accompanied by soil sample collection at defined depth intervals (0–10, 10–20, 20–40, and 40–80 cm).

Total REE contents in soils and biomass were determined by ICP-OES after microwave digestion, while the mobile fraction was quantified using BCR step 1 (acid-soluble/exchangeable) as a proxy for bioavailability. Bioaccumulation (BF) and translocation (TF) factors were calculated as indicators of REE uptake from soil and internal transport between plant organs.

The studied soils were characterized by high total contents of REEs within the following ranges (in mg $kg^{-1}$): La (1298–1441), Ce (1992–2178), Nd (634–696), Pr (188–205), Y (145.4–165.8), Sm (87.9–97.5), Eu (24.9–27.4), Gd (73.8–80.9), Tb (8.08–8.70), Dy (35.0–39.0), Ho (5.37–5.98), Er (11.6–12.2), Tm (1.14–1.22), Yb (5.07–5.45), Lu (0.53–0.55), and Sc (<1). The summed lanthanides approached ~4365–4798 ppm (≈0.44–0.48%). This pronounced enrichment identifies phosphogypsum-derived technogenic soils as a substantial secondary REE reservoir and a promising target for assessing REE bioavailability, uptake, and internal redistribution in silver birch, as well as the feasibility of REE phytomining on phosphogypsum waste heaps.

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# Thermally Enhanced Biodegradation Mechanisms of Chloroethenes and BTEX Co-Contaminants in Groundwater: Insights into Microbial Functional Gene Enrichment and Biogeochemistry

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## ABSTRACT

Chloroethenes and BTEX compounds (benzene, toluene, ethylbenzene, and xylene) are typical organic pollutants commonly found in industrial sites in China, and their co-contamination has become a key concern in the field of site remediation. In-situ bioremediation has been proven to be a cost-effective and environment-friendly approach for co-contaminated sites remediation. Furthermore, thermally enhanced biodegradation (TEB), referring to thermal treatment with elevated temperatures was promising in promoting microbial growth and metabolic activities thus biodegradation efficiency. However, the microbial degrading for chloroethenes and BTEX under natural anaerobic condition is unclear, and TEB effects on co-contaminants biodegradation behaviors and indigenous microbial communities also remain largely unexplored.

In our study, the typical intermediates dichloroethene (DCE), vinyl chloride (VC) and nontoxic end-product ethene of tetrachloroethene (PCE) and trichloroethene (TCE) biodegradation were detected under natural condition, implying the presence of complete reductive dechlorination. Moreover, the detection of organohalide-respiring bacteria (OHRB), reductive dehalogenase genes (*tceA*, *vcrA*, *bvcA*) and also BTEX-degrading genes (*tmoA* and *cat2,3*) provided supporting evidence for biodegradation potential of co-contaminants in groundwater with indigenous microbial community. Subsequentially, a series of TEB experiments under anaerobic condition were conducted to evaluate the effects on the biodegradation of TCE and benzene co-mingled contaminants using indigenous microbial consortiums. The results showed that the highest TCE biodegradation rate, 0.35 μmol $L^{-1}$ $day^{-1}$, was observed at 30 °C, whereas the biodegradation of benzene was enhanced to a less extent. The functional gene analysis results revealed that enriched *tceA* and *tmoA* genes contributed to TCE and benzene biodegradation at 30 °C, respectively. Additionally, it was found that benzene was degraded via anaerobic oxidation pathway with identification of intermediates, phenol, toluene and benzoate, along with sulfate reduction and iron reduction under co-contamination condition. Furthermore, functional degrading genera were also enriched at evaluated, consistent to the enhanced biodegradation behaviors. This study provides TEB mechanisms from insights of the microbial and functional genes responses of native consortia, underscoring the potential of TEB as a practical and sustainable remediation technology for complex chlorinated solvents and BTEX co-contaminated groundwater.

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# Estimating Petroleum Hydrocarbon Plume Volume and Mass from Sparse and Zero-Inflated Soil Data Using INLA-SPDE

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## ABSTRACT

Remediation costs are strongly controlled by the volume and mass of contaminated soil, making accurate plume delineation essential for effective remediation planning and cost reduction. However, most contaminated soil sites are characterized by small sample sizes, sparse borehole networks, and zero-inflated concentration data, posing substantial challenges for conventional plume estimation approaches. Traditional geostatistical methods, such as Kriging, are particularly sensitive to borehole number, spatial configuration, and depth-specific replicates, and are unable to explicitly represent preferential flow processes.

In this study, we extend the Integrated Nested Laplace Approximation with a Stochastic Partial Differential Equation (INLA-SPDE) framework to estimate petroleum hydrocarbon (PHC) plume volume and mass, focusing on benzene and the CCME F1 fraction. A tracer-based covariate was incorporated to represent preferential flow effects within the spatial model. This application represents a novel extension of INLA-SPDE beyond its prior use for general soil properties to contaminated site assessment.

Model performance was evaluated using three synthetic plumes with known geometry and two real remediation sites, and compared against Hurdle and Kriging-based approaches across 100 repeated estimation runs. Results demonstrate that the INLA-SPDE framework provides robust and stable plume estimates under extremely sparse sampling conditions, achieving accurate volume and mass estimation with as few as 5 boreholes and maintaining prediction errors within 50% of ground-truth References. Incorporation of the tracer covariate substantially improved plume predictions for the more hydrophobic and strongly sorbing CCME F1 fraction, while offering limited improvement for the more mobile benzene.

Overall, this study highlights the suitability of INLA-SPDE as a decision-support tool for contaminated site management, particularly in data-limited environments where conventional geostatistical methods fail to provide reliable plume estimates.

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# Potential bacterial resource for bioremediation of organochlorine pesticides and flame retardants recognized from forest soil across China

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**ABSTRACT**

Microbe-mediated remediation becomes a desire method for removal of persistent organic pollutants (POPs) due to its eco-friendly and sustainable nature. The improvement of practical feasibility requires constructing comprehensive species pool, while it is still limited by the rapid recognition of potential bacterial resources from environment. Here, based on the relative abundances of bacterial OTUs and pollutant concentrations, we established indexes to assess their tolerance to organochlorine pesticides (OCPs) and flame retardants (FRs) that are atmospheric transported and naturally accumulated in forest soil via forest filter effect. By exploring the tolerance pattern from tropical to temperate forests across China, we demonstrated that diversity, community composition, and relative abundances of POP-tolerant bacteria were significantly related to POPs' distribution and concentration. By recognizing over a hundred of genera composed of POP-tolerant species, we found that OCP-tolerant taxa were wide-distributed, while bacterial communities were more responsive to the contamination level of FRs and FR-tolerant taxa were accumulated along the increase of FRs pollution. Our indexes successfully recognized well-known POPs-degrading genera, including *Rhodococcus*, *Bacillus*, *Arthrobacter*, *Stenotrophomonas*, and *Pseudomonas*, as well as a series of versatile taxa affiliated with families Ktedonobacteraceae, Acetobacteraceae, Solirubrobacteraceae, and Nocardiaceae, which were extremely rare and likely ignored in laboratory-scale experiments. Together, our findings provide valuable clues to expand the library of POPs-degrading candidates that is helpful in screening bacterial resources for bioremediation.

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# Historically Exposed Soil Microbiomes Serve as Living Bioenhancers for Antibiotic Remediation

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**ABSTRACT**

Studying the complex responses of natural microbiomes is crucial for fully understanding the environmental impacts of antibiotics. Current research largely focuses on the inhibitory effects of antibiotics, but lacks in-depth insights into the resilience and functional feedback mechanisms of indigenous microbial communities under combined antibiotic stress.

This study took mixtures of sulfonamide and tetracycline antibiotics—frequently detected in groundwater—as the research object, and investigated their effects on soil microbiomes with different exposure histories: two types of soils, namely pre-exposed soils containing residual antibiotics and pristine control soils. The results showed that these antibiotic mixtures exert strong selective pressure, significantly altering the structure and succession of microbial communities. Network analysis further identified keystone taxa that are essential for maintaining community stability and function.

Most importantly, microbiomes with a historical exposure history not only exhibited greater resilience, but also showed significantly enhanced antibiotic degradation capacity. This finding indicates that such microbiomes can serve as efficient "living bioenhancers" with inherent potential for bioremediation applications. Moreover, this conclusion was validated using genome-scale metabolic modeling (GSMM) technology, which revealed that the metabolic interactions among these microbes are more intense. The findings of this study establish a critical link between chemical pressure and microbial adaptive functions, and provide a new paradigm for applying pre-adapted microbiomes in environmental restoration and risk assessment.

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# Biochar and microorganism-assisted remediation of brownfields

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## ABSTRACT

Brownfields contaminated with heavy metals and polycyclic aromatic hydrocarbons (PAHs) pose significant environmental and human health risks. Biochar- and microorganism-assisted bioremediation has emerged as a promising, sustainable approach for restoring such sites. Biochar, produced from the pyrolysis of biomass, improves soil physicochemical properties, immobilizes heavy metals through adsorption and complexation, and reduces PAH bioavailability. Simultaneously, biochar provides a favorable habitat and carbon source for indigenous and introduced microorganisms, enhancing microbial survival, activity, and diversity. Microorganisms contribute to remediation through metal transformation, sequestration, and enzymatic degradation of PAHs. The synergistic interaction between biochar and microorganisms enhances contaminant stabilization and degradation while improving soil fertility and ecosystem recovery. The assisted phytoremediation of heavy metals was tested under controlled greenhouse conditions. Different variants: single microorganisms' application, raw biochar, inoculated with microorganism biochar and water absorbing material (BIOWAG) with biochar were applied to contaminated soil, and white mustard (*Sinapis alba* L.) plant was used as a testing plant. Results of the experiment showed that use of BIOWAG with biochar component and microorganism inoculation was the most efficient method of supporting plant growth and inducing metal accumulation in upper plant parts, thus supporting the phytoremediation process of metal removal, with no adverse effects on the plant. This integrated strategy offers an effective, low-cost, and environmentally friendly solution for the remediation and sustainable reuse of polluted brownfields.

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# Remediation potential of oil-contaminated soils, under biochar and mineral salts influence

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## ABSTRACT

An important area of research is the development of agrobiotechnologies based on the management of the natural soil microbiome, the creation of microbial preparations that decompose xenobiotics, and the use of microbiological methods to increase the proportion of biological nitrogen in plant nutrition. The development of environmental technologies is crucial for improving land management and protecting the environment. This research focuses on assessing the genetic potential of soil microbial communities and their application in the development of fundamental soil science and environmental technologies. Promising areas are formulated related to the use of microbial potential of soils for the purpose of bioremediation of territories from ecotoxicants, development of technologies of self-purification of soils based on stimulation of natural microbial communities, as well as application of microbial preparations of biodegradation of petroleum products. The purpose of this work was to assess the metabolic potential of soils contaminated with petroleum hydrocarbons for processes aimed at the destruction of hard-to-reach compounds and the transformation of oxidized and reduced forms of nitrogen when biochar or mineral easily soluble salts are added. Samples of chernozem, chestnut, gray forest, peat, sod-podzolic soils, podzol, as well as buried soils and permafrost soils were studied. Using gas-chromatographic, molecular-biological, and bioinformatics methods, the metabolic potential of soils contaminated with petroleum hydrocarbons was assessed for processes aimed at the destruction of hard-to-degrade compounds and the transformation of oxidized and reduced forms of nitrogen when biochar or mineral salts were applied. Adding organic biochar to oil-contaminated samples of podzolic soils, mineral compounds of potassium chloride and nitrate salts to chernozem, or a complete mineral fertilizer ($N_{40}P_{50}K_{50}$) to peat soil with incomplete liming (0.5 hydrolytic acidity) resulted in a significant increase in the number of copies of functional genes (*xylE, alkB, alkM, Bss*) involved in the decomposition of petroleum hydrocarbons and the reduction of residual petroleum products. It has been shown that the addition of biochar to oil-contaminated soils increased the number of copies of genes that mark the nitrogen cycle (*amoA, nirK,* and *nifH*), which can be useful for developing effective bioremediation strategies for oil-contaminated areas. For each of the studied soils, the most oil-resistant bacterial genera were identified.

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# Characterizing Temperature-Dependent Dissipation Kinetics of Co-Mingled Contaminated Soils

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## ABSTRACT

Petroleum hydrocarbons (PHCs), including gasoline and diesel, are widespread soil contaminants that degrade soil quality and pose ecological and human health risks. Understanding their dissipation under realistic environmental conditions, such as nutrient availability, temperature, and moisture levels, helps identify conditions that enhance natural degradation and guide low-cost, minimally intrusive in-situ remediation strategies. This study characterized the dissipation kinetics of co-mingled gasoline- and diesel-contaminated soils under varying temperatures (4 °C, 14 °C, and 24 °C). Additional investigated treatment conditions included a variation of moisture content (35%, 65%, and 90% of field capacity) and nutrient concentrations (no nutrient addition, addition of macronutrients only, and addition of macro and micronutrients Soil was spiked to 53,600 mg $kg^{-1}$ total PHC (TPH), including 14,500 mg $kg^{-1}$ of volatile petroleum hydrocarbon (VPH) components. Soil samples were collected on Days 0, 7, 14, 28, 49, and 77 for residual PHC concentrations in the soil. The first-order model provided the best fit for the dissipation trends observed in the study. For the VPH fraction, dissipation half-lives decreased as temperature increased, from 29.7 days at 4 °C to 20.0 days at 14 °C and 8.5 days at 24 °C, with corresponding first-order rate constants increasing from 0.0233 to 0.0346 and 0.0820 $day^{-1}$. Total PHCs showed a similar temperature response but with slower kinetics, with half-lives declining from 180.5 days at 4 °C to 141.7 days at 14 °C and 82.8 days at 24 °C, alongside rate constants increasing from 0.00384 to 0.00489 and 0.00837 $day^{-1}$. Both the VPH and TPH showed a significant increase in degradation rates between 14–24 °C than between 4–14 °C, with VPH consistently displaying higher temperature sensitivity ($Q_{10}$ = 2.24 vs. 1.74 for TPH between 14–24 °C). At 24 °C, residual TPH and VPH were significantly higher at higher moisture levels. At 14 °C, both fractions had significantly lower residual concentrations at 35% field capacity. At 4 °C, no significant effect of moisture level was observed for TPH. However, VPH showed significant differences between the 35% and 90% moisture levels, with the lowest residual concentrations occurring at 35% field capacity. Nutrient effects followed a similar temperature-dependent pattern. Nutrient effects followed a similar trend. No significant nutrient influence was observed at 4 °C for both VPH and TPH, but at 14 °C and 24 °C, TPH removal was significantly higher with macro + micronutrient addition, whereas VPH removal was significantly higher under no-nutrient conditions.

These findings provide practical insight into how temperature, moisture, and nutrient conditions shape the dissipation of co-mingled PHCs in soil. By generating temperature-dependent kinetic parameters such as half-lives, rate constants, and $Q_{10}$ values under controlled but realistic conditions, this work supports more informed decisions when evaluating the potential for natural attenuation or planning low-impact in-situ remediation strategies in cold climates.

# Temporal Dynamics and Metabolic Profiling of Vetiver Root Exudates Under Atrazine Stress

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**ABSTRACT**

Root exudates are key mediators for plants to regulate the rhizosphere microenvironment and enhance the degradation of organic pollutants in soil. To clarify the response patterns of root exudates from *Chrysopogon zizanioides* under atrazine stress, a 60-day pot experiment was conducted to investigate the variations in root exudates of *Chrysopogon zizanioides* exposed to atrazine. Two treatments were set up: no atrazine addition (CK) and atrazine addition at a concentration of 2 $mg \cdot kg^{-1}$ (AT). Root exudate samples were collected on the 10th, 20th, 30th, 45th, and 60th days, respectively. Gas chromatography-mass spectrometry (GC-MS) was employed for compound identification and peak area quantification. The results were listed below:

1. During the 60-day incubation, a total of 24 classes of compounds were detected. The 10 most abundant classes were alkanes, alkenes, esters, alcohols, amides, ketones, acids, phenols, aldehydes, and benzenes in sequence, accounting for 34.33%, 16.96%, 15.74%, 6.22%, 4.02%, 3.74%, 3.50%, 2.68%, 2.53%, and 2.24% of the total number of compounds, respectively.
2. The total number of the four classes of compounds (alkanes, alkenes, esters, and alcohols) accounted for more than 70% of the total, and their abundance exhibited a unimodal distribution over time, peaking on the 30$^{th}$ day. The number of acids and nitriles was significantly higher in the middle and late stages of incubation (30–60 d) than in the early stage (10–20 d).
3. The five classes of compounds with relatively high relative concentrations were amides ((Z)-13-docosenamide, (Z)-9-octadecenamide), alkanes (docosane, 2,6,11-trimethyldodecane), esters (1,3-dimethyl 2-(pyridin-3-ylmethylidene), bis(2-methylpropyl) 1,2-benzenedicarboxylate), nitriles (oleanitrile), and acids (erucic acid) in sequence.
4. At the mid-stage of incubation (on the 30$^{th}$ day), the total compound number of root exudates, as well as the number of upregulated acids and alcohols, in the ATZ added treatment was higher than those in the ATZ non-added treatment.

In conclusion, ATZ exposure not only increased the total compound number of root exudates, but also specifically induced the massive secretion of compounds with potential detoxification or antioxidant functions, including acids and alcohols. This may be the key physiological mechanism for *Chrysopogon zizanioides* to adapt to ATZ stress and perform hyperaccumulation.

**Keywords:** Atrazine; *Chrysopogon zizanioides*; Root exudates

# Sequential Causal Machine Learning Assisted Design of Biochar for Laccase Immobilization

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**ABSTRACT**

The sequential causal relationships among preparation conditions, biochar properties, and immobilized laccase activity pose critical challenges in optimizing biochar preparation conditions for enzyme immobilization. Here, a novel sequential causal machine learning model was coupled with reinforcement learning to optimize preparation conditions and ensure immobilized laccase activity. For biochar properties and immobilized laccase activity, excellent prediction accuracy was achieved utilizing Random Forest ($R2 = 0.72 \pm 0.11$) and Adaptive Boosting ($R2 = 0.86 \pm 0.12$). Interpretability analysis elucidated that preparation conditions exerted nonlinear effects on biochar properties and immobilized laccase activity, mainly driven by raw material types and specific surface area. Reinforcement learning optimization of biochar design achieved 2.18 U/g laccase immobilized activity with agricultural waste as optimal raw material under optimized preparation conditions. Experimental validation showed that the optimized biochar achieved advantageous immobilized laccase activity ($2.03 \pm 0.07$ U/g), environmental adaptability, storage stability, and effective benzo[a]pyrene removal ($51.25 \pm 0.87\%$). This study provides a feasible approach to analyze the nonlinear causal sequential relationships among biochar preparation conditions, biochar properties, and immobilized laccase activity, enabling targeted design of biochar preparation conditions to optimize immobilized laccase activity.

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# Effects of Amendments on the Anaerobic Bioremediation of Organohalides in Contaminated Soil and Groundwater

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**ABSTRACT**

Organohalide and petroleum hydrocarbons are commonly found in soil and groundwater at contaminated oil and gas industrial sites. Specifically, tetrachloroethylene (PCE) and its daughter compounds (trichloroethylene, dichloroethylene, and vinyl chloride) along with co-contaminants benzene and toluene pose numerous health risks to humans and wildlife. The objective of this research is to evaluate the effectiveness of biostimulant amendments in increasing the rate of dechlorination of PCE and its daughter compounds in the presence of benzene and toluene.

Soil and groundwater were taken from a brownfield industrial site in Edmonton, Alberta, Canada. Microcosms were prepared with soil and groundwater from the site and then spiked with benzene, toluene, and PCE. Triplicate microcosms were left untreated or treated with biostimulants- ERDENHANCED™, or lactate. The microcosms were kept in an anaerobic chamber to maintain reducing conditions, and regular GC measurements of concentrations of contaminants and other gases (methane, carbon dioxide, ethene) were done by headspace injection. qPCR for bacterial species *Dehalococcoides* and 16s microbial sequencing were performed to examine community shifts throughout the experiment. Microcosms have been re-spiked and re-amended to examine repeatability. Microcosms amended with ERDENHANCED™ had increased microbial presence compared to the lactate treatment or the unamended microcosms. Amended microcosms had faster removal rates compared to unamended microcosms. This work provides insights on the role of amendments in remediation and their complex interactions within the soil microbiome, namely the selective enriching of dechlorinating microbes.

# In Situ Enhanced Reductive Dechlorination for Chlorinated Aliphatic Hydrocarbon–Contaminated Sites

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**ABSTRACT**

Chlorinated aliphatic hydrocarbons (CAHs) are widely used industrial solvents whose long-term leakage has caused extensive soil and groundwater contamination. Due to their high density, low solubility, and persistence, CAHs migrate as dense non-aqueous phase liquids into aquifers and low-permeability zones, forming recalcitrant contamination sources. In situ enhanced reductive dechlorination (ERD) is a low-carbon and sustainable remediation strategy that relies on anaerobic microbial processes to transform CAHs into non-toxic end products such as ethene. However, its field application is often constrained by incomplete dechlorination, toxic intermediate accumulation, limited electron-donor availability, and insufficient microbial stability.

Field investigations at an aged CAH-contaminated site revealed that long-term contaminant stress strongly reshaped subsurface microbial communities. With increasing depth, higher CAH concentrations and anaerobic stability were associated with increased microbial diversity, greater community convergence, and more stable co-occurrence networks. Deep soils were enriched with organohalide-respiring bacteria, fermentative microorganisms, and iron- and sulfate-reducing bacteria, forming functionally cohesive assemblages adapted to CAH stress. Community assembly analysis showed that deterministic processes dominated microbial structuring under high contamination, whereas stochastic processes were more important in shallow soils.

Guided by these site-scale insights, a highly efficient 1,1,2-trichloroethane (1,1,2-TCA)-dechlorinating microbial consortium was enriched from contaminated groundwater. The consortium rapidly and completely transformed 1,1,2-TCA to ethene via vinyl chloride as the sole intermediate, achieving dechlorination rates exceeding those previously reported. Functional analyses revealed a clear division of labor, with Trichlorobacter catalyzing dihaloelimination of 1,1,2-TCA and Dehalococcoides completing vinyl chloride hydrogenolysis, supported by fermentative and syntrophic partners supplying key metabolites and cofactors.

To overcome electron-donor transport limitations in low-permeability media, a nano-emulsified vegetable oil (nanoEVO)–based biostimulation strategy was developed. The nanoEVO exhibited small droplet size, high stability, and sustained electron-donor release. Bioreactor experiments demonstrated that nanoEVO significantly enhanced indigenous microbial activity, increased Dehalococcoides abundance and reductive dehalogenase gene expression, and promoted efficient and complete removal of 1,1,2-TCA and its intermediates.

Overall, this study demonstrates that ERD is an eco-engineering process driven by contaminant-selected microbial communities and can be effectively regulated through targeted biostimulation. Integrating site-scale microbial ecology, functional consortia, and engineered electron-donor delivery provides a robust framework for improving in situ bioremediation of CAH-contaminated environments.

**Acknowledgments**

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# Dual inhibition mechanisms drive antagonistic effects during phenanthrene and pyrene co-degradation by Pseudoxanthomonas: Pathway competition and substrate pReferences

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**ABSTRACT**

The biodegradation of polycyclic aromatic hydrocarbons (PAHs) involves complex metabolic interactions among multiple degradation pathways. However, how interactions among different pathways influence the overall degradation efficiency remains poorly understood. In this study, *Pseudoxanthomonas* sp. G3, an efficient degrader of phenanthrene (PHE) and pyrene (PYR), was used to investigate pathway interactions under mixed-PAH conditions. Genomic and metabolomic analyses revealed that strain G3 degrades PHE and PYR through three pathways: the phthalate pathway (with phthalic acid as the dead-end product), a shared catechol pathway, and the benzoate pathway. Notably, PYR induced the benzoate pathway, representing a previously unreported metabolism of PYR by bacteria. Integrated analyses revealed that PHE inhibits PYR degradation via dual mechanisms. Specifically, PHE preferentially utilizes the PYR-induced benzoate pathway, thereby diverting metabolic flux and impeding PYR degradation. Moreover, the benzoate pathway further inhibits the catechol pathway, intensifying suppression of PYR degradation. These findings elucidate mechanistic insights into the interactions among the biodegradation pathways under mixed-PAH stress and provide a theoretical basis for targeted improvement of the efficiency and predictability of mixed-PAH degradation.

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# The Fundamentals of Disturbed Land Reclamation

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**ABSTRACT**

The problems of restoration of disturbed territories and biocenoses, which can effectively neutralize the negative consequences of mineral development, remain very relevant at present. The formation of disturbed areas in which almost all components of the natural environment are disturbed and destroyed makes it possible to study the restoration of ecosystems from scratch, which is of great theoretical interest. It is also necessary to recognize that the development of methods for the effective restoration of disturbed lands without fundamental knowledge of the laws of restoration of individual components of ecosystems is impossible. Many years of research on technologically disturbed areas, carried out in various natural and technogenic conditions, made it possible to formulate the fundamental foundations of reclamation work. 1. Determination of the main characteristics and individual specifics of technogenic landscapes. 2. Formulation of the remediation goal and determination of performance targets. 3. Assessment of reclamation resources and prospects for their use to create favorable conditions for landscape restoration. 4. Calculation of reclamation efficiency and monitoring of restored areas. 5. Assessment of soil and ecological state taking into account the level of restoration of soil and vegetation cover.

**Keywords:** reclamation, soils, technogenic landscapes, ecosystems

# Ecological restoration of semi-arid, PTE-enriched toxic mine tailings through organic amendments and microclimatic regulation via fascines

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## ABSTRACT

Ecological restoration of potentially toxic mine tailings in semi-arid environments poses major challenges due to extreme climatic conditions and poor soil quality (high salinity, low fertility, weak structure, and high levels of potentially toxic elements -PTEs- such as metals and metalloids). Since conventional remediation techniques are often ineffective or economically unfeasible in these contexts, integrated and nature-based solution (NBS) strategies that combine soil conditioning with microclimatic regulation are suitable alternatives to promote sustainable recovery.

This study presents a multifactorial field experiment integrating organic amendments (biochar and municipal organic solid waste) and microclimatic regulation through forest brush barriers (fascines) to enhance soil recovery in PTE-polluted tailings in the Cartagena–La Unión mining district (SE Spain). Several plant species (*Pinus halepensis*, *Tetraclinis articulata*, *Atriplex halimus*) were placed to simulate revegetation conditions and assess the suitability of these restoration strategies for plant establishment. Over one year, seasonal dynamics of physicochemical and biological indicators were monitored to evaluate how these factors interact to improve soil functionality and resilience.

Organic amendments significantly increased pH, total and soluble organic C and N, enzymatic activities (β-glucosidase and dehydrogenase), microbial respiration, and invertebrate feeding activity, while reducing water-soluble Zn and Cd concentrations. Simultaneously, fascines induced contrasting microclimatic conditions that influenced soil biochemical responses. Shady microsites exhibited lower soil temperatures in warm months, greater biological activity, and higher organic C and N contents, although no consistent improvement in soil moisture was detected. These results indicate that microclimatic orientation modulates biological processes and can enhance amendment performance under semi-arid constraints.

The combined application of organic inputs and fascines generated more stable soil conditions and greater biological resilience than either approach alone. This integrated strategy reduced PTEs mobility and improved soil structure and functionality, facilitating native vegetation establishment and promoting natural recovery. Therefore, the proposed approach represents a low-cost, circular, and scalable solution for restoring degraded mining areas and mitigating the extra limitations of semi-arid climates.

**Acknowledgments**

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# Exogenous Chemicals Used to Alleviate or Salvage Plants under Flooding/Waterlogging Stress: Their Biochemical Effects and Perspectives

**ABSTRACT**

Plant flooding/waterlogging stress (FWS) can be a threat to food security worldwide due to climate change. To mitigate its potential devastation, numerous exogenous chemicals (ECs) have been used to demonstrate their effectiveness on alleviating FWS for the last 20 years. This review has summarized the most recent findings on use of various ECs as either nutrients or regulatory substances on crop plants under FWS and their roles involved in improving root respiration of seedlings, optimizing nutritional status, synthesizing osmotic regulators, enhancing the activity of antioxidant enzymes, adjusting phytohormone levels, maintaining photosynthetic systems, and activating flood-tolerance related gene expressions. The effect of ECs on alleviating plants under FWS proves to be beneficial and useful but rather limited unless they are applied on appropriate crops, at the right time, and with optimized methods. Further research should be focused on use of ECs in field settings and on their potential synergetic effect formore FWS tolerance

**Keywords:** flooding stress, waterlogging, exogenous chemicals, biochemical metabolisms

# Ultrafast and high-capacity gold retrieval via cascade reduction

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**ABSTRACT**

Selective gold extraction using absorbents represents a promising sustainable technology for wastewater treatment in gold mining and the smelting process. To facilitate convenient gold recycling, the absorbed gold ions necessitate an effective gold ion reduction process to simultaneously convert $AuCl_4^-$ into metallic gold.

The extraction of Au ions necessitates the successive dechlorination of $AuCl_4^-$ to $AuCl^-$ (i.e., $AuCl_4^- \rightarrow AuCl_3^- \rightarrow AuCl_2^- \rightarrow AuCl^-$) and the nucleation to Au particles. However, a method for precisely controlling stepwise reaction conditions to dynamically match the multistage reduction for ultra-efficient gold recovery has been in suspense. Herein, the aminated hydrocarbon with inherent hydroxyl (-OH) performed rapid stepwise $AuCl_4^-$ dechlorination by cascade reduction. The tandem active sites of -OH and amine ($-NH_2$) showed an unprecedented reduction rates (0.091 g/min/mg) while still maintained high gold reduction capacity (3652.0 mg/g). The high propensity for dehydrogenation revealed that -OH serves as a quick-acting electron donor that initiates a cascade reaction by lowering the energy barrier from $AuCl_3^-$ to $AuCl_2^-$. Then, $-NH_2$ serves as a powerful capture site with complementary electrons for the subsequent dechlorination from $AuCl_2^-$ to $AuCl^-$, which finally nucleates to gold clusters. Notably, -OH and $-NH_2$ periodically supported cascade reduction and thus could selectively extract more than 99.9% of gold ions, even from a strong acidic solution. These findings will inspire innovative designs for sequence-controlled reactions in scalable gold recovery.

**Keywords:** Mining drainage, gold recovery, cascade reduction

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# Comparison for physico-chemical properties of restored soil with two types of vegetation at abandoned coal mine in Gangwon province, South Korea

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## ABSTRACT

Waste rock piles generated during coal mining and preparation processes have caused various problems, including slope collapse and the occurrence of acid mine drainage. Due to declining coal demand, the number of active coal mines in Korea decreased from 347 in 1988 to complete closure expected by 2025. Consequently, it is essential to focus on the restoration processes and their effects on abandoned coal mine sites today.

To manage waste rock piles in coal mines, restoration efforts such as covering the underlying waste materials with soil, seeding understory vegetation and planting trees are being implemented. Although numerous studies have examined the restoration of abandoned coal mine sites using vegetation, research on how vegetation affects changes in soil properties by vegetation remains limited. Therefore, this study compared the physico-chemical properties of restored soil according to different vegetation types.

Organic matter inputs on the ground, soil depth, root size and root distribution in the soil profile, stone content, soil texture, soil pH, cation exchange capacity (CEC), total organic carbon (TOC), total nitrogen (TN), carbon-to-nitrogen ratio (C/N) and available phosphate (AP) were analyzed at an abandoned coal mine restored with two vegetation types: understory vegetation or tree (*Betula pendula*)).

The root ratios in the soil profile ranged from 5% to 75% in the top soil layer, and from 1% to 40% in the underlying waste rock layer at the birch tree site. These values were higher than those at the understory vegetation site, where root ratios ranged from 1% to 50% in the top soil layer and from 7% to 10% in the underlying waste rock layer. In the top soil layer, AP and TN were 21.34 ppm and 0.13%, respectively, at the birch tree site, compared to 14.84 ppm and 0.07% at the understory vegetation site, showing a significant difference ($p < 0.05$). CEC was 21.41 cmol/kg at the birch tree site, and 17.05 cmol/kg at the understory vegetation site, indicating a highly significant difference ($p < 0.0001$).

This study demonstrates that planting trees is a more effective long-term restoration method for improving soil quality in abandoned mining areas than seeding understory vegetation. Tree planting site exhibit higher levels of key nutritional factors, such as CEC, TN, and AP. Additionally, this research provides data to support future restoration efforts and monitoring of abandoned coal mine sites.

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# Upcycling Rare Earth Hyperaccumulator Biomass into Functional CaS:Ce Phosphors: A Coupled Remediation–Utilization Strategy for Degraded Rare Earth Mine Soils

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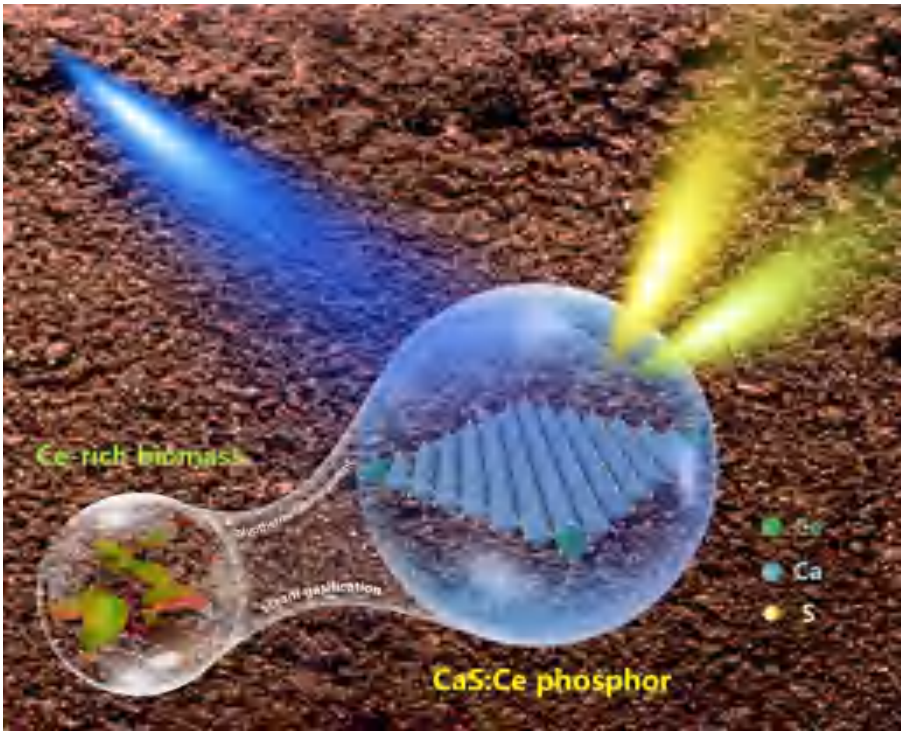
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## ABSTRACT

Rare earth mine tailings and associated soils are often severely degraded, posing long-term ecological risks and constraining land reclamation efforts. Phytomining, which employs hyperaccumulator plants to extract rare earth elements (REEs) while simultaneously improving soil quality, has emerged as a promising remediation–utilization strategy for mined lands. However, the lack of efficient and economically viable approaches to valorize REE-rich biomass remains a major barrier to large-scale implementation. Here, we develop a direct in situ doping strategy to convert cerium (Ce)-enriched hyperaccumulator biomass into color-tunable CaS:Ce phosphors while co-producing renewable syngas. Through solvothermal pretreatment with sulfuric acid and ethanol, Ce, Ca, and S are selectively enriched into a reactive char matrix, which is subsequently transformed into luminescent CaS:Ce phosphors via steam gasification. The resulting phosphors exhibit broad green–yellow emission with high photoluminescence quantum yields (18.5–37.4%). Compared with conventional REE recovery pathways, the process reduces energy demand by 89.1%, carbon emissions by 88.1%, and overall costs by 90.5%. By integrating soil remediation through REE phytoextraction with high-value utilization of hyperaccumulator biomass, this approach offers a sustainable pathway for restoring degraded mined lands while producing functional REE-based materials. The findings demonstrate a scalable remediation–resource recovery model that aligns with circular-economy principles and enhances the feasibility of phytotechnology-based restoration of mined soils.



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# The dependency of spontaneous vegetation growth on soil and tailing material properties of mine residue deposits at different climates in Namibia

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**ABSTRACT**

What drives the growth of spontaneous vegetation on mine residue deposits across different climates in Namibia? Is spontaneous vegetation a solution for cost-effective greening of mine residue deposits in Namibia? Would irrigation improve the growth of spontaneous vegetation? Could semi-purified mine waste water be used for such irrigation? Which kind of soil material does spontaneous vegetation need for optimal growth? These questions are being investigated at two locations in Namibia with different climatic conditions in order to develop sustainable and climate-adapted management strategies for the greening of mine residues and the use of mine water. One site is the mine residue deposit of Rosh Pinah lead and zinc mine in Southern Namibia. The other location comprises the mine and smelting residue deposits of the copper mine and smelter in Tsumeb in Northern Namibia.

At Rosh Pinah, with an average annual precipitation of only about 24 mm, species such as *Caroxylon vermiculatum, Zygophyllum spec.* or *Stipagrostis spec*. are colonizing the mine residue deposit. In contrast to this arid climate, at Tsumeb, with an average annual precipitation of 563 mm, species such as *Dodenaea viscosa* or *Cambretum imberbe* or *Phoenix dactilifera* are spreading on mine residue deposits. At both locations, the plants only occur on sandy surface soils. Almost no vegetation is occurring where the upper layer of the deposits consists of silt or salt crusts. Additionally, almost no vegetation occurs where black sand, gravel and stones have been used to cover the deposits to prevent dust resuspension. In vegetated areas, roots grow several decimeters deep into the mine residues. Thus, the local contaminations with high concentrations of copper, zinc or lead do not prevent plant growth as the study shows. Differences are much more found regarding soil texture and the related water balances in the most upper layer. Therefore, sensors are installed to record soil water dynamics at different depths of the deposits and kf and pF values are determined in the laboratory. The objective is to determine optimal soil conditions of the upper horizons for colonization by spontaneous vegetation. In a second step, on site field experiments will take place to elaborate the optimal thickness of these upper soil layers for plant growth. This experiment will also investigate the potential of mine water to be used for irrigation during the initial growth phase and to cope with extensive drought periods. The results will be made available through a decision matrix including the choice of plants, the usability of local water resources and the needs for soil meliorations for application to other mine residue deposits.

**Acknowledgments**

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# Biochar-loaded AM fungi coupled with Arundo donax enable targeted red mud remediation via valency-specific metal detoxification and soil function recovery

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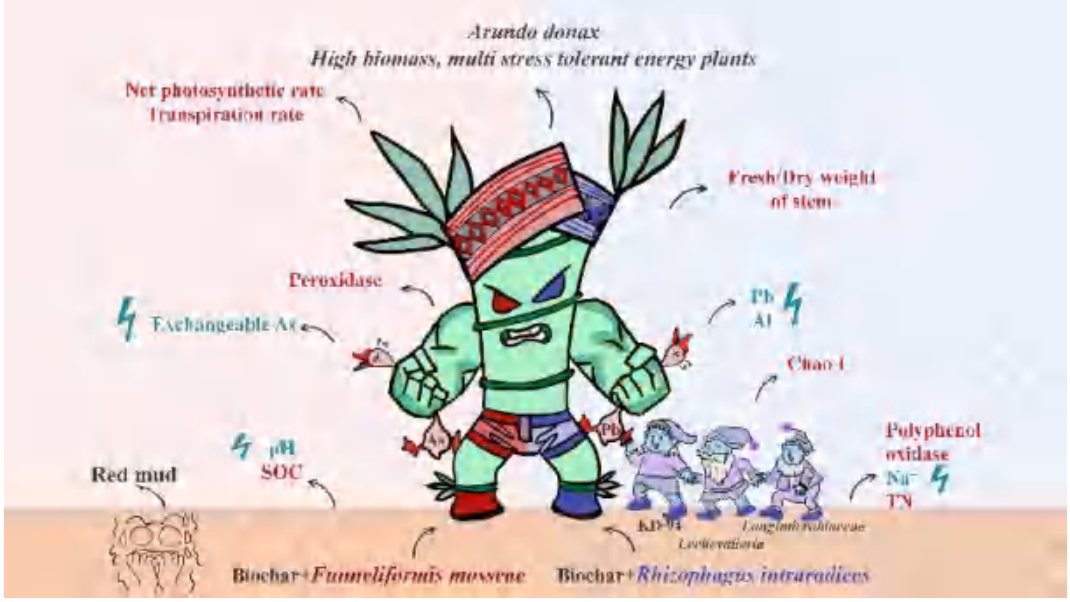
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## ABSTRACT

Red mud, a saline-alkaline and metal-contaminated byproduct, poses severe ecological risks. This study elucidates the synergistic remediation mechanisms of biochar (BC) combined with arbuscular mycorrhizal fungi (AMF) in an Arundo donax-soil system. We specifically investigated biochar loaded with Funneliformis mosseae (BC-FM) and that loaded with Rhizophagus intraradices (BC-RI). The BC-FM treatment significantly enhanced the plant antioxidant system and photosynthetic capacity while reducing the content of exchangeable arsenic (As) and soil pH, thereby inducing a "photosynthesis enhancement-As immobilization" synergy. In contrast, the BC-RI treatment markedly increased plant biomass and soil microbial α-diversity, while simultaneously reducing the contents of soil lead (Pb) and sodium ions ($Na^+$), and enhancing alkaline phosphatase activity-thus demonstrating a "Pb fixation-microbial diversity-soil phosphorus (P) activation" cascade. Rhizosphere network analysis identified key bacterial genera, with Longimicrobiaceae driving soil organic carbon accumulation in the BC-FM treatment and Lechevalieria enhancing alkaline phosphatase (ALP) activity in the BC-RI treatment. These findings support a novel "fungal species-heavy metal valency matching" principle, where RI preferentially targets cationic Pb,while FM targets anionic As. This principle establishes a three-dimensional synergistic model: "Heavy metal transformation – concurrent salinity-alkalinity mitigation – microbial function activation". The results provide a foundational strategy for zonal red mud remediation: applying BC-RI in Pb-dominated areas and BC-FM in As-contaminated areas.



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# Formation and Migration Patterns of Polycyclic Aromatic Hydrocarbons in Underground Coal Fires: A Case Study of a Typical Coal Fire Zone

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**ABSTRACT**

Coal seam fires represent a persistent global disaster that damages both resources and ecosystems in coal- producing nations. China suffers from some of the world's most severe coal fires, with over 200 active fire zones in its central and western regions, covering a total area exceeding 50 million m². Our investigation, involving more than 200 samples from over 20 fire zones in Xinjiang, Ningxia, Inner Mongolia, etc (see 1), revealed abnormal groundwater pH and polycyclic aromatic hydrocarbon (PAH) enrichment around these areas. In newly covered soil layers at the formerly extinguished Wuda fire zone in Inner Mongolia (successfully controlled during 2011-2015), the Liuhuanggou fire zone in Xinjiang (controlled in 2000, now re-ignited), and the Sangonghe fire zone in Xinjiang (controlled in 2003), total PAH concentrations were 30 to 100 times above background levels (see 1), with a peak value of 165 mg/kg. This underscores the urgent need for fundamental research into the reaction kinetics of organic pollutants from underground coal fires and collaborative mitigation strategies.



Figure 1 Field survey of soil pollutants in coalfield fire zones

This study employs molecular reaction kinetics to investigate reaction dynamics, examining real-time structural transformations during reactions. It addresses uncertainties in organic pollutant formation pathways and the lack of coordinated control theory under high-temperature, oxygen-deficient conditions characteristic of coal fires. A stepwise PAH formation pathway driven by radical recombination—specifically 'cleavage-condensation and dehydrogenation-cyclisation'—is proposed. Furthermore, a critical transformation threshold for PAHs was established: within the high-temperature, oxygen-deficient coal fire environment, oxygen concentration ≥3% and temperature ≤400℃ (See 2). Addressing the complexity of pollutant migration driven by the dynamic evolution of coal fire fissures, we pioneered a thermal buoyancy-driven model for organic pollutant migration. This breakthrough overcomes the limitations of traditional gravity-field pollution diffusion, providing crucial theoretical support for understanding and controlling the migration of organic pollutants from coal fires.

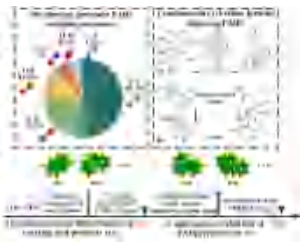


Figure 2: Mechanism of PAH Production and Prevention and Control Technologies in Coalfield Fire Zones

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# The removal mechanism of Pb2+ from wastewater by phosphorus-modified biochar

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**ABSTRACT**

Lead (Pb) is a highly toxic and persistent environmental pollutant that poses significant risks to human health. Biochar has demonstrated effective Pb immobilization, and phosphorus-modified biochar exhibits enhanced adsorption capacity for $Pb^{2+}$. In this study, rice straw biochar (BC) was modified using phosphorus-containing compounds at different ratios to produce five variants: unmodified BC, phosphate rock powder blended with rice straw at 1:1 (SBC1) and 1:5 (SBC5), and calcium dihydrogen phosphate mixed at 1:1 (NBC1) and 1:5 (NBC5). Isothermal adsorption tests revealed that BC, SBC1, and SBC5 followed the Langmuir model, with maximum adsorption capacities of 60.00 mg/g, 106.19 mg/g, and 273.08 mg/g, respectively, while NBC1 and NBC5 conformed to the Freundlich model, exhibiting maximum capacities of 217.91 mg/g and 251.36 mg/g. Kinetic experiments indicated that $Pb^{2+}$ adsorption by all biochars followed pseudo-second-order kinetics, with BC primarily relying on chemisorption. Post-adsorption, the equilibrium solution pH decreased, and phosphorus concentrations in modified biochars initially declined before a slight increase. SBC5 and NBC1 exhibited superior Pb adsorption and removal efficiency, predominantly through precipitation, whereas unmodified BC immobilized Pb via chemisorption. These differences may be attributed to variations in phosphorus content and specific surface area. XRD analysis confirmed that no new phases formed in BC after the reaction with Pb, whereas SEM-EDS detected the presence of Pb in the residues. In contrast, phosphorus-modified biochars formed $Pb_5(PO_4)_3Cl$, with Pb accumulating on surfaces or within pores at high concentrations. FTIR spectra indicated minimal peak shifts in BC but notable changes in modified biochars: C-O exhibited a blue shift, while C=O and P-O displayed red shifts, suggesting precipitation of Pb-containing compounds. These findings provide a theoretical foundation for rice straw waste recycling and soil Pb pollution remediation.

**Key words** phosphorus modified biochar, biochar, $Pb^{2+}$, pH

**Acknowledgments**

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# Vetiver Grass Induced Changes in Soil Acidity, Electrical Conductivity and Soil Organic Carbon in Mine-Affected Soils over two Rehabilitation Periods

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## ABSTRACT

Rising carbon emissions have contributed to drastic weather changes that threaten agricultural productivity, while mining activities in South Africa have further degraded arable soils leading to soil acidity and reduced fertility. These pressures threaten food security and socioeconomic stability, underscoring the need for sustainable strategies that mitigate atmospheric carbon and restore soil health. Vetiver grass has potential, however, its effectiveness in mine-degraded soils remains under investigated globally. Therefore, this study assessed the effects of vetiver grass on soil acidity, electrical conductivity (EC) and organic carbon (OC) in mine-affected soils using a 6×2×2 factorial microplot experiment at the University of Limpopo. The first factor comprised of six composite soil samples collected in proximity to a Gold Mine. The second factor included the presence or absence of vetiver grass, while third factor consisted of two rehabilitation periods (3 and 6 months). Pre and post soil samples were analysed for soil pH in water ($H_2O$) and potassium chloride (KCl), EC and OC. Furthermore, root and shoot vetiver biomass was determined post each rehabilitation period. Results showed that all the three factors and their interaction significantly ($p<0.05$) influenced OC, EC, and soil pH. Rehabilitating the soil for 3 months led to significant increases in OC and EC but resulted in a decline in acidity, particularly in forest soils. Extending the rehabilitation to 6 months generally reduced these soil variables but enhanced soil acidity, root and shoot vetiver biomass. The decline, however, did not go below the initial baseline before the rehabilitation process. Increased vetiver growth was strongly negatively correlated with the decline in EC and soil pH, indicating active modification of the soil environment through root exudation and ion uptake. Overall, this study shows that vetiver grass significantly alters soil properties during rehabilitation by reducing EC, neutralizing acidity and increasing OC. However, the magnitude of these changes is highly dependent on the initial condition of the mine-affected soils. As extended rehabilitation periods revealed the potential re-emergence of soil acidity, 3 months is the most effective period for the regulation of soil pH and EC.

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# Root acquisition-defense strategies of pioneer plants in heavy metal contaminated mining areas

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**ABSTRACT**

Metal mining has driven widespread ecosystem degradation globally, producing severely degraded habitats characterized by landscape destruction, heavy metal contamination, nutrient depletion, soil physical structure deterioration, and water erosion. Primary succession on such substrates is exceedingly slow, and ecological restoration is often limited to a small subset of pioneer species. Root functional traits, which are phenotypic traits reflecting plant growth, reproduction, survival, and responses to environmental changes, hold significant importance for understanding how plants adapt to and modify their environments. Variation in root traits strongly influences plant growth strategies. However, the belowground strategies that enable the establishment and persistence of pioneer plants in metal -contaminated and toxic substrates remain poorly understood.

Here, we compiled the China Pioneer Plant Trait Database (CPPTD) by synthesizing information from hundreds of publications, integrating global trait databases (e.g., TRY, GROOT), and incorporating field surveys conducted in mining areas of South China. We classified pioneer species into functional groups based on life form and mycorrhizal type, and quantified species positions within the conventional two-dimensional root economics space (RES), defined by the “collaboration” and “conservation” gradients, using key root traits, including specific root length, root diameter, root tissue density, and root N concentration. In addition, we evaluated defense-related trait trade-offs using root carbon composition together with metal bioconcentration factors.

The results indicate that pioneer species broadly conform to global RES trade-offs, representing the “collaboration” gradient from do-it-yourself to outsourcing, and the “conservation” gradient from fast to slow. However, interspecific differences between pioneer and non-pioneer species are generally small along nutrient-acquisition gradients, suggesting that nutrient acquisition is not the primary strategy driving pioneer colonization in highly contaminated habitats. In contrast, defense-related traits are strongly associated with root heavy metal bioconcentration factors, revealing tight linkages between root carbon allocation patterns and bioconcentration potential. Field observations of the dominant pioneer species *Miscanthus sinensis* further suggest that inorganic defense-related traits may trade off with organic defense traits, such as root carbon composition, and contribute more strongly to tolerance under heavy metal stress.

Overall, these findings support an expanded acquisition–defense trait trade-off framework for species colonizing contaminated mining areas, providing a trait-based mechanism for clarifying pioneer strategies and informing species selection for ecological restoration and phytoremediation.

**Acknowledgments**

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# Ecological package-driven early reclamation of open-pit mines in arid and semiarid regions: Insights from soil bacterial communities, functional genes and physicochemical properties

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**ABSTRACT**

Open-pit mining in arid and semi-arid regions causes severe soil degradation, and the initial restoration stage (0–5 years) is critical for ecosystem recovery trajectory and efficiency. Harsh environments and limited water resources lead to slow natural recovery, highlighting an urgent need for effective artificial interventions. This study aimed to explore the impact of short-term artificial restoration on soil microbial communities and functional traits, providing scientific support for early reclamation of similar open-pit mines. Using a space-for-time substitution approach, a three-tiered evaluation framework (soil bacterial communities – microbial functional genes – physicochemical properties) was established. High-throughput metagenomic sequencing analyzed four treatments: 3-year natural recovery (CK), 2-year (ER2) and 5-year (ER5) artificial "ecological package" restoration, and undisturbed native desert steppe (TC). The ecological package included drought-tolerant native seeds, water-retaining hydrogel, slow-release NPK fertilizer, and composite microbial inoculant, adapted to arid and semi-arid conditions. Results showed that compared to CK, the ecological package did not alter bacterial evenness (Shannon, Simpson indices) but significantly increased species richness (Chao1, ACE indices). It reshaped community composition: ER2 and ER5 enriched r-strategist taxa like *Proteobacteria* and reduced *Actinobacteria*, associated with soil nutrient availability. Network analysis revealed stronger interspecific interactions in ER2 (11,118 edges) than CK (9,823 edges), while ER5 (6,160 edges) stabilized, approaching TC (8,148 edges). Functional genes involved in carbon (*abfA, accA*), nitrogen (*nifA, nxrA, nxrB,nosZ, nirS*), and phosphorus (*ppa, ugpA, phoB,gcd*) cycling were significantly enriched in ER2, indicating early "functional activation". By year 5, gene abundance moderately decreased, reflecting a transition from high-energy activation to efficient low-energy steady state. Redundancy analysis identified soil organic carbon, ammonium, and nitrate as core drivers. A phased nutrient management strategy was proposed: prioritize carbon and nitrogen supplementation in 0–2 years to stimulate microbial activity, and targeted phosphorus supplementation after 5 years to sustain soil functionality. This study clarified the dynamic evolution of microbial communities and functional traits during early restoration. The three-tiered framework and phased strategy provide scientific basis and practical guidance for ecological reclamation of open-pit mines in harsh arid and semi-arid regions.

# High-Throughput Detection Method for Microplastics Based on Fluorescence Spectroscopy and Machine Learning

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**ABSTRACT**

The ecological risks posed by microplastics (MPs) are increasingly severe. MPs have been confirmed to be widely present in various complex environmental media, including marine and freshwater systems, sediments, soils and organisms[1]. However, significant knowledge gaps remain in the current scientific understanding of key scientific issues regarding the formation, migration, and transformation processes and mechanisms of MPs in actual environmental media. This is largely attributed to the lack of technologies for rapid and accurate identification and quantitative detection of low-concentration MPs in complex media[2]. Currently, there is still a lack of methods capable of achieving imaging alongside rapid, high-throughput qualitative and mass concentration detection[3]. To address this gap, this study developed a detection method based on the autofluorescence of microplastics.

In this study, a novel aging treatment method was applied to 7 common types of MPs in the environment, significantly altering their fluorescence properties. Based on the fluorescence spectrum data of these 7 MPs and machine learning algorithms, a high-throughput rapid detection technology framework for MPs was established. A dedicated fluorescence spectrum database was built by the 3921 sets of fluorescence spectrum data of the 7 MPs collected by confocal laser scanning microscope (CLSM), and a stacked model was further constructed. This model achieved an identification accuracy of 89% for the 7 MPs. To verify the method's applicability, mixed MP samples, commercial MP samples, and river water spiked samples were tested. The results showed that the recognition rates of all samples exceeded 80%, demonstrating the method's excellent environmental adaptability and target recognition performance. Furthermore, a three-dimensional (3D) model was constructed to analyze the 3D fluorescence images of MPs collected by CLSM for calculation of MP volume. Combined with the fluorescence qualitative results of microplastic types, particle density was determined to achieve quantitative analysis of microplastic mass. Moreover, the fluorescence method demonstrated 86% accuracy in lake water sample detection, validated by Fourier transform infrared microscope (μ-FTIR) results. Quantitative analysis achieved ng-level detection precision per particle. This validation confirms the method's applicability to actual environmental samples. Additionally, imaging times for qualitative and quantitative detection were 50 s and 20 s respectively within a single field of view (1 mm * 1 mm), significantly faster than traditional μ-FTIR detection speeds.

In summary, this research centers on the auto-fluorescence characteristics of aged MPs, integrating fluorescence spectral imaging and 3D fluorescence imaging technologies. It utilizes machine learning for qualitative identification and three-dimensional modeling for quantitative analysis, ultimately establishing a high-throughput rapid detection system for MPs. This technique provides a novel tool for the rapid screening and accurate quantification of MPs, and is expected to offer crucial support for research on MP migration mechanisms and the standardization process of pollution risk assessment.

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# Beyond Detection: An Intelligent Raman-Based Exploration of the Microplastic Full-Lifecycle

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## ABSTRACT

The global proliferation of microplastics has evolved from an environmental crisis into a profound challenge for human health. Characterizing these particles across complex matrices—from soil environments to biological tissues—requires a leap "Beyond Detection" toward holistic lifecycle analysis.

This report discusses an intelligent Raman framework designed to facilitate full-lifecycle investigations. Integrating automated identification with single-cell functional analysis—conceptualized as "Raman+"—this methodology provides high-fidelity characterization and multidimensional insights into particle identity and biological interaction. Such a framework spans the trajectory from environmental fate to biological endpoints, establishing an analytical foundation for systematic, closed-loop studies of the microplastic continuum while enhancing research fidelity and throughput.

**Keywords:**
Raman Spectroscopy, Microplastics, Raman+, Full-Lifecycle Analysis, Environmental Traceability, Biological Effects, Single-Cell Sorting

**Biography:**

**Li Bei**, Professor and Ph.D. Advisor at the National Key Laboratory of Advanced Manufacturing for Optical Systems, Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP), Chinese Academy of Sciences (CAS), and the Academic Leader of the Biophotonics Discipline.

He formerly served as a Senior Research Fellow at the University of Oxford, UK. Currently, he is an expert on Industrial Development Projects under the Ministry of Industry and Information Technology (MIIT), a Council Member of the Microscopy Instrument Branch of the China Instrument and Control Society, a Committee Member of the Environmental Microbiology Professional Committee of the Chinese Society for Microbiology, Director of the Jilin Provincial Key Laboratory of Rapid Biological Raman Detection and Artificial Intelligence, Director of the Jilin Provincial Engineering Laboratory of Single-Cell Raman Technology, and a Member of the 14th Changchun Municipal Committee of the Chinese People's Political Consultative Conference (CPPCC). He has been selected for the National Overseas Talent Program and the National Financial Support Project for High-Level Returned Overseas Talents by the Ministry of Human Resources and Social Security. Furthermore, he is the recipient of multiple provincial honors, including the Changbaishan Distinguished Leading Talent, Top-Notch Innovative Talent (Tier 1), and Jilin Province's National-Level Leading Talent (Category B), as well as the Special Allowance of the Jilin Provincial Government. After returning to China in late 2017, he founded Changchun Changguang Chenying Biomedical Scientific Instrument Co., Ltd. (Changguang Chenying) and serves as its General Manager.

Professor Li possesses years of practical research experience in optomechatronics. Prior to returning to China, he studied and worked in several top-tier laboratories in the UK, participating in and completing multiple EU and UK scientific research projects with total funding exceeding £13 million. Over the past five years, he has led and participated in more than 30 national, provincial, and ministerial-level research projects, helping his team secure over 20 million RMB in research grants. He has published over 50 papers in renowned international journals, including *Environmental Science and Technology*, *Biomedical Optics Express*, *Talanta*, *Advanced Healthcare Materials*, and *Applied and Environmental Microbiology*, and holds 22 granted invention patents and 1 international patent. Currently, his work focuses on the research, development (R&D), and industrialization of optical technologies and equipment for biomedical applications. The single-cell sorter independently developed by his team is the world's first commercialized single-cell isolation product based on Laser-Induced Forward Transfer (LIFT) technology. In addition, his team has successfully completed the R&D and industrialization of Raman spectroscopy equipment, ultrafast confocal imaging systems, particulate matter detectors, and colony phenotype detection and picking workstations.

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# Weathered microplastics trigger metal transformation

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**ABSTRACT**

Plastic debris has emerged as a significant hotspot for elemental biogeochemical transformations. In this presentation, we demonstrate that photo-weathering of plastics facilitates the formation of surface carbonyl groups, which mediate the reduction of silver ions to silver nanoparticles. Concurrently, oxidative weathering of plastics under light-independent conditions induces the production of methylmercury in environments. This methylation proceeds via an biotic reaction cascade comprising three-sequential steps: (1) release of plastic-derived dissolved organic matter (P-DOM), (2) complexation between P-DOM and Hg(II), an (3) intramolecular transfer of methyl groups. Model estimates demonstrate that polypropylene in the water column produce MeHg via this abiotic pathway at rates from 1.4×10−5% d−1 to 7.4×10−2% d−1 in China and 2.0×10−6% d−1 to 9.9×10−3% d−1 in other regions of the world. Plastic debris is therefore a significant, albeit hidden, driver of abiotic methylmercury formation in waters under darkness. Our study uncovers novel pathways through which the ongoing plastic pollution alters metal cycling, posing a burgeoning threat to planetary health.

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Huang YN, Dang F, Yin YG, Fang GD, Wang YJ, Yu GH, Zhou DM, Xing BS. Weathered microplastics induce silver nanoparticle formation. *Environmental Science & Technology* Letters. 2022. 9, 179-185.

# Precise tracking of nanoparticles in plant roots

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**ABSTRACT**

Precise determination of nanoparticle fate in plants is a central challenge in sustainable agriculture. However, conventional method approaches often produce ambiguous results because of background interference, probe leakage, sample-preparation artifacts, and insufficient spatial resolution. Here, we establish a dual-step analytical strategy for precise tracking of nanoparticles in plant roots by integrating fluorescence imaging at the tissue level with electron microscopy at the cellular level. In this framework, vascular bundles and fluorescence co-localization are used as internal References for uptake visualization, while mass-thickness contrast and metal-doped particles provide direct ultrastructural evidence for nanoparticle localization and internalization.

Using this strategy, we systematically investigated the behaviors of both carbon-based nanoplastics and metal-based nanoparticles in representative plant systems. In *Arabidopsis thaliana*, nanoplastics with different surface charges exhibited distinct uptake patterns, tissue distributions, and phytotoxic effects, accompanied by inhibited root growth and enhanced reactive oxygen species accumulation. In duckweed, nanoplastics entered through both roots and fronds, again showing strong charge-dependent differences in uptake and physiological responses. Importantly, Pd-doped nanoplastics enabled direct verification of nanoplastic uptake in root tissues, providing a robust solution to the long-standing challenge of accurately identifying polymeric nanoparticles in planta.

We further reveal that magnetite nanoparticles can enter roots through an epidermis-based pathway that is not restricted to lateral-root emergence sites, extending the current understanding of exogenous particle entry into plants. In addition, nanoparticle coating chemistry strongly affects interactions with root exudates, thereby regulating particle behavior, root uptake, and biological outcomes. Small-molecule-coated magnetite nanoparticles effectively alleviated iron chlorosis in multiple plant species.

Overall, this work provides a reliable framework for tracking of nanoparticles in plants and demonstrates that surface chemistry is a key determinant of nanoparticle uptake, transport, and function. These findings offer new guidance for nanoplastic risk assessment and the rational design of plant-beneficial nanomaterials.

# Impact of microplastics on nitrate reduction in agricultural soils

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**ABSTRACT**

Microplastics (MPs) are ubiquitous in agricultural soils and can indirectly affect soil nitrogen (N) cycling by altering soil physicochemical properties and microbial communities. Previous studies have shown that MP exposure often leads to a decrease in soil nitrate-N ($NO_3^-$-N) content; however, the relative contributions of different transformation processes, such as denitrification, anaerobic ammonium oxidation (Anammox), dissimilatory nitrate reduction to ammonium (DNRA), and microbial assimilation, remain difficult to distinguish and quantify. To address this, this study selected non-biodegradable MPs (polyethylene, PE; polyvinyl chloride, PVC; polystyrene, PS), biodegradable MPs (polylactic acid, PLA; polyhydroxyalkanoates, PHA), and aged MPs as research objects. Controlled incubation experiments, employing $^{15}N$-tracing combined with membrane inlet mass spectrometry (MIMS) in paddy soils and the robotized continuous-flow incubation system (RoFlow) in upland soils, were performed to investigate the effects and mechanisms of MPs on $NO_3^-$-N transformation in agricultural soils. The results showed that in paddy soils, short-term exposure to MPs (PE, PVC, and PS) significantly stimulated denitrification and Anammox rates but inhibited the DNRA process, leading to increased N loss. In contrast, long-term exposure to aged PE-MPs suppressed denitrification. Further mechanistic analysis revealed that with prolonged exposure, aged MPs increased carbon (C) availability, while $NO_3^-$-N in paddy soils remained chronically limited; the resulting C and N supply imbalance constrained the activity of denitrifiers. In upland soils, MPs derived from PVC greenhouse films did not alter gaseous N emissions under aerobic conditions, but the abundance of denitrification functional genes increased significantly. Denitrification potential assays under anoxic conditions confirmed that such MPs promote nitrous oxide ($N_2O$) emission. This is attributed to the high content of plasticizers (phthalate esters, PAEs) contained in the MPs, which can be utilized as a C source by heterotrophic denitrifiers, providing electron donors. Another type of MPs, tire wear particles (TWPs), promoted complete denitrification in upland soils; however, their leachate inhibited $NO_3^-$-N transformation and $N_2O$ reduction, thereby increasing $N_2O$ emission. Analysis of dissolved organic matter (DOM) molecular composition revealed that labile DOM molecules favored complete denitrification. Moreover, the assimilation of $NO_3^-$-N under C source input induced by MPs should not be overlooked. For example, biodegradable MPs (e.g., PHA) primarily drive microbial assimilation leading to a decrease in $NO_3^-$-N, rather than denitrification loss. This indicates that biodegradable MPs favor reactive N retention, but simultaneously stimulate soil C emissions and increase the proportion of labile DOM, with fungi playing a dominant role in this process. In summary, this study systematically reveals the differential mechanisms by which various types of MPs regulate $NO_3^-$-N transformation in agricultural soils, offering insights into C and N availability, DOM molecular characteristics, and microbial communities, and providing a scientific basis for assessing the ecological risks of MPs in agricultural soils.

**Acknowledgments**

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# Migration Behaviors of Typical Microplastics in Soil with Different Textures by Rainfall Induced Surface Runoff

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**ABSTRACT**

Microplastics, as a new type of pollutant, are widely present in aquatic environments, soil, air, and other ecosystems. Rainfall is the most direct and efficient means of forming surface runoff and is considered a significant driver of atmospheric microplastic deposition. However, it is important to note that ground-based microplastics remain the primary source of microplastics in runoff. Soil is a highly complex multiphase system. Its structure, composition, and intricate micro-ecological environment determine that the migration behavior of microplastics within soil is extremely complex and highly uncertain. Microplastics entering soil via rainfall runoff may cause accumulation, thereby weakening soil water retention capacity, altering physicochemical properties, disrupting biodiversity, and inhibiting plant and animal growth. Soil microplastic accumulation forms the material basis for pollution, while its ongoing migration process is a critical factor affecting soil ecological quality. This study employs artificial rainfall simulation experiments to investigate microplastic migration in soils of varying textures. It analyzes migration mechanisms for microplastics of different particle sizes under varying rainfall intensities, reveals the impact and patterns of rainfall runoff on soil microplastic migration, and assesses how rainfall intensity, soil texture, and microplastic particle size influence migration behavior. Rainfall intensity significantly influenced runoff generation and microplastic loss in soils of different textures, with smaller-sized microplastics exhibiting greater sensitivity to rainfall intensity changes. In sandy loam, loam, and clay loam soils, runoff generation increased rapidly during the initial rainfall phase before stabilizing. Across all soil textures, microplastic loss decreased with increasing rainfall duration, and higher rainfall intensity resulted in greater microplastic loss within the same timeframe. Initial runoff generation increased rapidly in all soil textures during the early rainfall phase before stabilizing. Microplastic loss decreased with longer rainfall duration, with higher intensity yielding greater loss. Sandy loam exhibited the highest loss, followed by loam, and lowest in clay loam, reflecting differences in soil particle composition and pore structure. Increased rainfall intensity promoted vertical migration of microplastics, with smaller particle microplastics exhibiting more pronounced migration. Sandy loam showed the highest migration rate, while clay loam had the lowest. Rainfall intensity, migration depth, and runoff volume significantly influenced loss rates, with their interactions collectively affecting microplastic migration behavior.

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# Anthropogenic activities and hydrologic environment of Danjiangkou Reservoir regulate soil microplastics in the water level fluctuation zone

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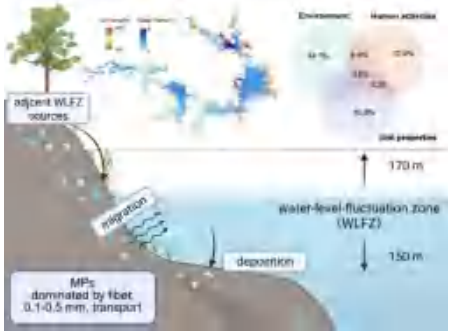
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**ABSTRACT**

The Danjiangkou Reservoir, the second largest reservoir in China, serves as the water source for the Middle Route of the South-to-North Water Diversion Project. As a new type of pollutant, the MPs in the Danjiangkou Reservoir may pose significant risks to the drinking water safety of millions of people. Particular attention should be paid to soil MPs in the water-level fluctuation zone (WLFZ) of Danjiangkou Reservoir, as this ecotone intercepts upstream pollutants and regulates substance transport. The seasonal water level fluctuations could transform this zone into a significant source or sink for reservoir MPs. However, the distribution and migration of MPs in this ecologically critical zone remain poorly characterized.

To address this knowledge gap, this study selected the WLFZ (150-170 m) of Danjiangkou Reservoir and conducted large-scale sampling of soil and shoreline water samples before the rainy season. The aim was to investigate the distribution and characteristics of MPs in the WLFZ and to identify the key influencing factors. The results showed that the abundance of soil MPs in the WLFZ ranged from 144 to 1050 items/kg. The MPs abundance in the Dan Reservoir was higher than that in the Han Reservoir. Specifically, the mainstream exhibited higher MPs abundance than the tributaries in the Dan Reservoir, whereas the tributaries in the Han Reservoir were larger than the mainstream. The abundance of soil MPs in bare land and farmland was significantly higher than in grassland and woodland. The MPs are predominantly the size of 0.1-1 mm, the shape of fibers and pellets, the color of transparent and blue, and the polymer types are mainly polypropylene (PP) and polyethylene (PE). Among all influencing factors, human activities (distance from village and population density) and land use were identified as determinants of MPs abundance. The hydrological environment of the reservoir, including water level fluctuations, reservoir bays and banks, and mainstreams and tributaries, influenced the redistribution of MPs. Therefore, we emphasize the importance of controlling human activities and agricultural farming to prevent and control MP pollution. This study systematically reveals the distribution of MPs pollution in the WLFZ and provides a key scientific basis for the prevention and control of MPs pollution.

**Keywords:** Microplastics; Reservoir; Water level fluctuation zone; Spatial distribution; Influencing factors




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# Microplastic transport in soil by nematodes

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**ABSTRACT**

The ubiquitous distribution of microplastics (MP) has emerged as a global environmental concern, amplified by their migration into soil through various pathways, including water flow and bioturbation. As the most abundant animals on Earth, soil nematodes are vital to soil ecosystem functioning and may also influence the spreading of the smallest MP in soil, which remains underexplored. Here, we examined transportation of small MP (≤10μm) by several bacterivores nematode species, and examined the underlying mechanisms using Petri dish experiments. All tested nematodes significantly enhanced the spreading of MP from the center of the dishes, with smaller MP (1 and 2 μm) transported further than larger ones (5 and 10 μm). Over 21 days of cultivation, Caenorhabditis remanei showed the highest transport capacity, moving 10 ng of MP at a mean distance of 3.56 cm for 1 μm MP, 3.73 cm for 2 μm MP, 1.03 cm for 5 μm MP, and 0.45 cm for 10 μm MP. Behavioural observations revealed that all nematodes ingested and defecated 2 μm MP and transported 1-10 μm MP through surface adhesion to, and detachment from the cuticle. Cuticle adhesion emerged as the primary mechanism for nematode mediated MP transport. The relationship between nematode traits and the transportation of 2 μm MP was further examined across nine nematode species. Correlation analysis indicated that the nematodes' ability to transport MP was significantly associated with their mobility ($r = 0.881$, $p = 0.002$) and minimum body length ($r = 0.760$, $p = 0.018$). This study provides the first evidence that nematodes may play a crucial part in the redistribution of small MP. Similar transport mechanisms of MP are likely to occur also in (especially light textured) soils, and nematode mediated MP transport in soil is currently ongoing, and will also be presented.

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# Friend or foe? Can microplastics ever be our ally?

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**ABSTRACT**

Microplastic research on soils over the past decade has drawn a clear picture: The complexity of soils combined with the complexity of microplastics results in an immense variety of different impacts on terrestrial properties and organisms. Microplastics with their diverse shapes, polymer types and sizes can react with the dynamic biotic and abiotic systems of soils in countless ways. While numerous negative effects have been reported, such as reduced plant growth (Li et al., 2023) and enzymatic activity (Zhao et al., 2021), microplastics appear to also have positive effects on the soil environment. For instance, they may improve soil aeration (Rillig et al., 2021), contribute carbon to the soil matrix (Qiu et al., 2022) and even reduce greenhouse gas emissions (Ren et al., 2020). These findings could imply that microplastics may be beneficial to terrestrial ecosystems rather than only detrimental. But is it that simple?

Our paper offers a discussion on the severity and immediacy of microplastics and whether they could be a solution to certain soil and environmental issues by considering the negative and positive effects of microplastics and drawing comparisons to other contaminants and adjacent areas, from which lessons could potentially be learned.

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# From field to greenhouse: evaluating microplastics pollution and its potential impact on Mediterranean agricultural soils

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**ABSTRACT**

Microplastics (MPs) are increasingly recognized as emerging contaminants in terrestrial ecosystems, yet their effects on soil health and plant performance remain poorly understood. Terrestrial environments, particularly agricultural soils, are considered major sinks for MPs due to their persistence and accumulation. These particles can affect soil structure, microbial activity, and plant development, but the underlying mechanisms are still largely unexplored.

In agricultural systems, MPs can enter soils through various management practices such as irrigation with reclaimed water, application of sewage sludge and compost as fertilizers, the use of plastic films for mulching, or atmospheric deposition. Once incorporated, they may alter soil physical and biological properties, potentially compromising soil fertility and productivity.

To better understand these processes in Mediterranean agroecosystems, this study aims to assess microplastic contamination in agricultural soils of Catalonia (NE Spain) and to investigate relationships between MP's abundance and composition, soil physicochemical properties, fertilization regimes, and management intensity. Soil samples were collected from fields with different crops, soil types, and management practices. MPs were extracted through density separation and organic matter removal, and polymers were identified using Laser Direct Infrared (LDIR) spectroscopy. Soil parameters including pH, organic carbon, organic matter, nutrients, and texture were also analyzed.

Findings from this first phase will inform the design of controlled greenhouse experiments, where soils will be spiked with environmentally relevant concentrations of MPs to study their effects on soil health, microbial communities, and plant growth. Preliminary results will be presented, contributing to the development of standardized assessment methods and sustainable management strategies to mitigate plastic pollution in agroecosystems.

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# Comparative Degradation and Environmental Impacts of Biodegradable Mulch Films in Agricultural Soils of the United States and China: Toward Sustainable Plastic Management

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**ABSTRACT**

As an alternative to conventional polyethylene (PE) mulches, the rapid adoption of biodegradable plastics, such as polybutylene co-adipate co-terephthalate (PBAT), helps to prevent long-term soil contamination. However, the degradation performance and environmental consequences of these materials remain uncertain across diverse soils. This study incorporates cross-continental data from representative agricultural regions in China and the United States to examine the degradation dynamics, remaining micro- and nanoplastic formation, as well as effects of soil health and sustainability. Field experiments with consistent mulching and sampling methodologies were conducted in different regions in China and the U.S. Results showed that PBAT-based mulches may transiently increase micro- and nanoplastics concentrations in soils before reaching complete mineralization. Despite site-certain temperature and moisture regimes having a significant impact on breakdown rates, PBAT degradation substantially increased soil organic carbon and microbial biomass. Comparative analysis revealed regional disparities in policy and recycling frameworks: while U.S. efforts concentrate on field-based biodegradable product trials and certification, China's recent agricultural film recycling mandates have reduced PE residue accumulation. This study also emphasizes the need for integral surveillance of micro- and nanoplastics to encourage circular and environmentally sound plastic utilization.

# From snowpack to soil: microplastic pathways in alpine ecosystems

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**ABSTRACT**

Microplastics (MPs) are increasingly recognized as emerging pollutants even in high-elevation ecosystems, where they can be transported over long distances and accumulate within snowpack, soil, and aquatic systems. In this study, the occurrence and distribution of MPs in winter snowpack, alpine soils, and pond sediments was investigated in the LTER site Istituto Mosso (2650-2900 m a.s.l., NW Italian Alps), located inside a large ski area, aiming to assess deposition pathways and environmental sinks in high-elevation areas.

Surface snowpack was sampled during 2020-2021 and 2021-2022 winters, revealing comparable concentrations of ~200 MPs $L^{-1}$ of melted snow in both winter seasons. This similarity suggests that winter tourism, which was absent in the first winter season due to COVID-19 restrictions, did not substantially contribute to MP levels, highlighting atmospheric transport as the dominant source. In both years, MPs were mostly fibers composed of LDPE, consistent with long-range atmospheric transport due to their low density and airborne persistence. To investigate the fate of these MPs, soils, at three depths (0-5, 5-10, 10-20 cm), and sediments from two nearby ponds were sampled in summer 2024. A total of eight soil profiles were sampled, distributed across two typical alpine tundra vegetation communities: snowbed communities (SB) and *Carex curvula* grasslands (CC). SB sites are characterized by longer snow cover duration and deeper snowpacks than CC, potentially influencing MPs accumulation and retention. MPs were found in all soils, with higher concentrations in SB than in CC. The highest concentrations occurred in surface soil layers (6,200 and 4,000 MPs $kg^{-1}$ in SB and CC, respectively) and decreased markedly with depth, becoming negligible in the deepest layer. This vertical pattern indicates limited downward transport and preferential accumulation in the topsoil. MPs were also detected in pond sediments at both sites (~3,500-5,900 MPs $kg^{-1}$). LDPE fibers predominate across all soil and pond sediment samples.

Overall, these findings demonstrate that MPs reach remote, high-elevation environments mainly via atmospheric deposition, accumulate in seasonal snowpacks, and subsequently persist in the topsoil and ponds sediments. Their presence in both terrestrial and aquatic compartments suggests that alpine environments act as sinks for MPs, with potential implications for ecosystem functioning even in regions perceived as pristine.

**Acknowledgments**

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# Mineralization determines microplastic effects on soil organic carbon

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**ABSTRACT**

Replacing conventional plastics with biodegradable polymers may mitigate microplastic pollution, but the degradation of these carbon-based materials can alter the decomposition of native soil organic mater (SOM) through priming effects. The net impact of this interaction on soil carbon balance remains poorly constrained. Here, we used a stable isotope tracing approach, incubating C4 (maize)-based polylactic acid (PLA) microplastics in three C3-soils with varying COM content and microbial properties. We show that the PLA mineralization rate is the master variable that dictates the soil carbon priming and formations. In soils with low-to-middle SOM (~ 1.9 – 4.6%), high PLA mineralization rates (500-860% higher compared to the other soil) were coupled with a strong negative priming effect and efficient formation of new, stable mineral-associated carbon. In contrast, low PLA mineralization in the high-SOM soil (~ 5.8%) triggered a significant positive priming effect that overwhelmed new carbon formation, resulting a net loss of bulk soil carbon. We further found this mineralization-priming relationship in controlled by the native soil microbial functional capacity. Our findings reveal that the pre-existing soil properties determine whether biodegradable plastics will ultimately induce net carbon sequestration or net carbon loss. The mechanism that the soil carbon dynamics is depended on PLA mineralization mechanisms should be considered in further plastic biodegradation under changing soil environments.

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# Do biodegradable PBAT plastic films alter C–N coupling in ways that benefit soil functioning?

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## ABSTRACT

Considering that plastic mulch film is the most prevalent plastic used in agricultural soils, and that only in China approximately 10% of the total sown area is covered by plastic mulch (Hao, 2025), it is not surprising that the highest proportion of the mass of microplastics in crop soils comes from the use of conventional PE or PP mulch films, or the polymeric mixture of PP+PE (Zhu et al., 2022). Plastic residues from conventional mulch films in China commonly reach 60–300 kg/ha, and levels rise when films aren't properly removed or recycled (Xue et al., 2021).The removal of plastic mulch films from the crop is a time and energy consuming and adds a significant cost, as plastic can become entangled with crop roots, making complete removal harder, but also it may tear and break during removal or release micro- and nanoplastics during use, thus unintentionally leaving residues even when properly disposed of. Therefore, to combat the pollution left by conventional plastic films in soil, biodegradable plastic alternatives were proposed as an alternative to tackle plastic residue problems in croplands, with PBAT being the most commercialized biodegradable plastic film in China. Since these plastics are engineered to biodegrade, they are typically not removed after each harvest; instead, they are intended to be incorporated into the soil through tillage after use, facilitating for farmers the burden of the removal.

Although biodegradable plastics were expected to alleviate in part the white pollution provoked by mulch film use, a new environmental issue raised: during degradation, similar to conventional plastics, some of these biodegradable alternatives were demonstrated that can generate macro- and microplastics in even greater amounts than traditional plastics. However, these plastics residues are considered "short-term" microplastics as they continue further breakdowns and degrading. Yet while this happens, these biodegradable microplastics can also accumulate through successive cultivation cycles, break-down quickly by human handling that accelerates the fragmentation (Wang et al., 2021) during harvest and post-harvest, and incorporate into the soil and migrate by the action mainly of tillage mixing, and roots downward movement, but also can penetrate through soil cracks and pores spaces across soil layers (Wang et al., 2025) and by soil biota which also helps to break degrade further those plastics fragments (Huang et al., 2025), potentially causing adverse effects on soil health and crop growth.

Despite this, biodegradable microplastics can be considered a double-edged sword with a possible positive outcome: although certain types of biodegradable plastics may harm soil health, these residues are mainly composed of carbon that can be quickly used by microorganisms. As during degradation, the release of carbon and soluble compounds may induce a priming effect on soil carbon dynamics and, concomitantly, on nitrogen cycling. Consequently, the combined effects of their incorporation and biodegradation in the soil may provide an unexpected possible benefit to the soil micro-ecosystems; leading to a short-term increase in soil organic carbon and microbial carbon utilization.

The indirect effects of mulching on soil physicochemical properties arise from the plastic film direct contact with the soil and the subsequent accumulation of macro and microplastic residues within it. Mulch films can cause changes through the modification of the near-surface micro-climate by raising soil temperature, reducing water evaporation, and stabilizing moisture levels, which in turn alters nitrogen-cycling processes and changes the composition and activity of soil microbial communities (Sintim et al., 2019). Additionally, it affects the soil's microstructure by enhancing aggregate stability and modifying organic carbon forms (Yan et al., 2025), ultimately impacting directly soil carbon dynamics and indirectly soil nitrogen dynamics. Nonetheless, it is important to point out that changes in the soil of a field crop are the result of numerous processes, both abiotic and biotic, that take place over extended periods of time.

Authors such as Uzamurera et al., (2023) and Wang et al., (2024a) found that the incorporation of PBAT plastic residues into soil increases the content of a specific type of microplastics, biodegradable microplastics, which are less persistent than conventional ones but can nevertheless accumulate in significant amounts across the soil profile. Liu et al., (2025) found that those biodegradable microplastics when remaining in the field can indeed affect the SOC and its flux by providing a readily available source of labile carbon, which stimulates microbial activity and promotes short-term increases in soil organic carbon (SOC) levels, particularly in the form of particulate organic carbon (POC), and such microorganisms boost their activity that leads to a decrease in microbial biomass carbon and dissolved organic carbon and modifies mineral associated organic carbon and easily oxidable organic carbon, but negatively affecting soil enzymes associated to C and N. Suggesting that PBAT alters the form and flow of carbon rather than uniformly enhancing it. Those authors also indicated that plastic polymer type plays an important role in changing soil carbon-related indicators, with the change usually positively associated with biodegradable plastic microplastics. Similar results were found in Wang et al., (2024b) in which from analyses of long-term usage of biodegradable plastic the authors found that biodegradable plastics effectively increased soil organic carbon but decreased dissolved organic carbon and microbial biomass carbon when compared to PE conventional plastic mulch films.

However, evidence remains inconclusive. A laboratory study by Zhou et al., (2024) found that contrarily to the results seen on field experiments, introducing biodegradable microplastics into soil significantly increased dissolved organic carbon and microbial biomass carbon while significantly decreasing available nitrogen, nitrification rates, and β-glucosidase activity, and it had an insignificant effect on soil bacterial community structure, but it increased the relative abundance of some bacteria types. Sintim et al., (2020) also reported only minor effects of biodegradable plastics on soil microbial communities and functions, emphasizing instead that local climate, soil properties, and spatiotemporal variation are possibly the dominant drivers of carbon dynamics and physicochemical changes relative to the incorporation of biodegradable plastic mulches. With different crops in different places reporting different responses to biodegradable plastics.

In summary, without excluding the many field-scale drivers (crop growth stage, soil type, climate, and soil biota, including microbial and fungal communities), the application and subsequent tillage of biodegradable PBAT mulch films can induce dynamic and measurable shifts in soil carbon and nitrogen cycling. However, while PBAT mulch film microplastics residues may enhance short-term microbial processes and carbon inputs, it can also simultaneously promote the depletion of other forms of labile carbon and possibly limit nitrogen availability through microbial competition.

This presentation combines a field investigation that examined soils that used biodegradable PBAT for two consecutive years and were incorporated into the soil via tillage after maize harvest and compared with replicated treatments that used conventional PE mulch and no mulch as a control. And laboratory experiments that were conducted to assess how the only presence of microplastics derived from biodegradable PBAT mulch film or from PE mulch film in the soil affects soil organic carbon and labile carbon pools determinations. In field soils, we measured key carbon and nitrogen parameters, microorganisms activities (bacterial and fungal), and profiled soil and plastic metabolites at the time of sampling. Furthermore, in this work, we synthesize and critically discuss the existing literature to reconcile findings and clarify mechanisms through which biodegradable mulch incorporation may (i) increase soil organic carbon content, (ii) exert variable effects on labile carbon fractions, and (iii) impose detrimental effects on soil nitrogen pools and on soil enzymes associated with carbon and nitrogen cycling.

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# Identification and characterization of a biodegradable plastic mulch film degrading bacteria strain PBAT-1 in the soil

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**ABSTRACT**

Plastic mulch film can increase temperature, keep soil moisture and increase crop yield, widely used in agricultural production. However, due to the low recovery rate of mulch film recycling, the residual mulch film in the soil is easily fragmented or degraded into microplastics under light exposure, mechanical shear force and biological actions. Thus, plastic mulch film has become one of the essential sources of microplastics in soil. Polyadipate/butylene terephthalate (PBAT) is a biodegradable plastic polymer with ideal ductility, heat resistance, tear resistance and biodegradability. PBAT is one of the most active and best biodegradable materials in the research of biodegradable plastics, which has been widely applied to make biodegradable mulch films in recent years. However, studies have shown that PBAT only exhibits a good degradation effect under specific conditions, and the limited existing PBAT degrading strains are difficult to degrade PBAT mulching film effectively under mild environmental conditions. In this study, a few PBAT degrading bacterial strains were screened and isolated from the agricultural soil in Shandong province, which has a long history of plastic mulching film utilization. With a comprehensive analysis of the indicators, such as OD value of the bacterial cultures, the morphologic changes and weight loss rate of PBAT films, an efficient PBAT degrading bacterial strain was successfully isolated. The morphological, physiological and molecular identification of the strain were also carried out. Finally, the dynamic degradation of PBAT by the isolated strain was characterized, including the changes of molecular weight, roughness, chemical functional groups, hydrophobicity, surface morphology and biofilm composition characteristics of PBAT microplastics. The results of this study will provide a new bioresource for the biodegradation of PBAT plastics, and will provide a scientific basis for revealing the degradation mechanism of biodegradable plastic mulching films.

**Key words:** biodegradable plastics, PBAT, biodegradation, biofilm, enzymatic mechanism

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# Micro-nanoscale polystyrene and polyvinyl chloride co-exposure impacts the uptake and translocation of toxic elements and pesticides by lettuce and wheat

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## ABSTRACT

Micro-nanoplastics (MNPs) are widespread emerging environmental and food contaminants. The ability of MNPs to influence the fate and effects of other environmental pollutants (EPs) in terrestrial environments and in edible plants is a topic of great concern. Investigations were conducted to evaluate if co-exposure to MNPs (polystyrene, PS; 20 or 1000 nm; or polyvinyl chloride, PVC, <10 µm, unaged or aged) had an impact on the accumulation of other EPs (arsenic, lead, chromium, boscalid, PFOS) in lettuce or wheat. Under hydroponic conditions, lettuce was co-exposed to PS at 10 or 50 mg/L, and to 1 mg/L of each EP. In a soil study with lettuce, the PS and EPs were at 50 and 10 mg/kg, respectively. Phytotoxicity was enhanced by PS under both growth conditions, particularly nanoscale PS (nPS), although impacts were less in soil-grown plants. Nanoscale PS had a greater impact than microscale PS (µPS) on As fate; the As translocation factor from roots to shoots was increased 3-fold in plants co-exposed to nPS (50 mg/L). PS dose and size had a variable impact on boscalid uptake and translocation. Fluorescent microscopy analysis of lettuce co-exposed to MNPs and EPs suggests that nPS enters the roots and translocates to the leaves, while µPS remains mostly in the roots. Pyrolysis-GC/MS showed that in soil, EPs significantly increased the translocation of nPS in lettuce shoots from 4.43±0.53 to 46.6±9.7 mg/kg, while the concentration of µPS in the shoots was unchanged with EPs. Separately, co-exposure to unaged PVC increased the root and shoot accumulation of As, Cr, and Pb by 3.1-, 2.1-, and 1.5-fold, respectively; for aged PVC, the toxic element increases were 3.9-, 2.6-, and 2.1-fold, respectively. Soil-based experiments with wheat under similar co-exposure conditions are ongoing, as are molecular analyses to elucidate key mechanisms of action. These findings demonstrate that co-exposure of MNPs with other EPs can significantly impact co-contaminant accumulation and toxicity, presenting an unknown risk to humans and other receptors.

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# Impacts and degradation of microplastics (MPs) in agricultural soil

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**ABSTRACT**

As a typical type of emerging contaminants, microplastics (MPs) accumulated in soil not only affect the health of the soil-plant system, but also influence the biogeochemical processes and environmental effects of important biogenic elements such as nitrogen (N). However, relevant information about the effects of different types and properties of MPs on soil N migration/transformation and plant N uptake/metabolism is still limited. Therefore, we chose vegetable soils and lettuce (Lactuca sativa L.) as objects, and combined fields, pots and soil culture experiments to investigate the effects of different MPs on N migration and transformation processes in the soil-vegetable system. The impacts of different degradability of MPs (degradable: polylactic acid, PLA, and polybutylene adipate terephthalate, PBAT; undegradable: polyethylene, PE), doses and particle sizes on soil N transformation and lettuce N metabolism were investigated. It helps to reveal the impact mechanisms of typical MPs pollution on soil N-related biogeochemical cycles and to provide a scientific basis for agri-environmental risk assessment.

Furthermore, understanding MPs degradation in soil is also crucial for assessing its environmental impacts and pollution remediation. However, the ageing or degradation mechanisms of MPs mediated by soil iron oxides remain poorly understood. We investigated the degradation of polyethylene microplastics (PE-MPs) in agricultural soil amended with goethite (α-FeOOH) gradiently through quantitative incubation experiments. The results demonstrate that an appropriate dosage of goethite can significantly promote the degradation of PE-MPs in soil, ant the changes in goethite addition influence PE-MPs degradation indirectly by altering the transformation dynamics of iron oxides within the soil, rather than affect directly. Such study provides insights into the effects of goethite on MPs degradation in soil, implying possibility and potential of soil MPs pollution remediation by iron oxides.

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# Ecological Risk Assessment of Microplastics in Soil Based on Probability Distribution and Machine Learning

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## ABSTRACT

Soil microplastics (MPs) pollution, including tire wear particles (TWPs), has become a global environmental problem, which potential risks to soil ecosystems and human health are of increasing concern. However, because the heterogeneity and complexity of MPs distributed in the environment, conventional risk-assessment methods have difficulty accurately quantifying their ecological risks. In this study, based on a soil MPs three-dimensional characteristic abundance dataset, we constructed a three-dimensional probability density distribution model of MPs density, size and shape in soil using normal-inverse Gaussian (NIG), exponential and bimodal distribution models; by accurately converting between number concentration and mass concentration. Monte Carlo simulation together with the three-dimensional probability density distribution model were used to calculate the three-dimensional characteristics of MPs in soil. This study established a soil MPs three-dimensional characteristic-toxic effect dataset; based on the characteristics of soil MPs pollution, we adjusted threshold effect concentrations for the ingestible particle-size ranges of polydisperse MPs, optimized species sensitivity distribution (SSD) curves, and identified the earthworm *Eisenia fetida* as a sensitive soil organism. We further conducted a multi-level meta-analysis (experimental data n = 288) combined with an XGBoost model to quantify the effects of tire wear particles (TWPs) on soil microbial diversity, plant growth, animal growth, and greenhouse gas emissions, and to predict global-scale regional patterns covering 60 major countries across continents. Results show that microbial diversity decreased by approximately 8.27%; plant growth decreased by approximately 15.92%; soil animal growth decreased by approximately 18.29%; and overall greenhouse gas emissions increased by approximately 57.02%. High concentration, specific particle size, additives (6PPD and benzothiazoles (BTHs)), and heavy metals (Zn) are significant modifying factors; soil physicochemical properties and concentration are the main covariates. Model projections indicate significant heterogeneity in impacts across latitude, developmental level and climatic conditions; a 1.5 °C warming scenario and future vehicle-growth scenarios exacerbate risks in certain regions. The study indicates that TWPs exhibit cross-trophic amplification effects and pose potential threats to soil function and climate regulation, and that follow up mechanistic experiments as well as the establishment of monitoring and remediation standards are needed.

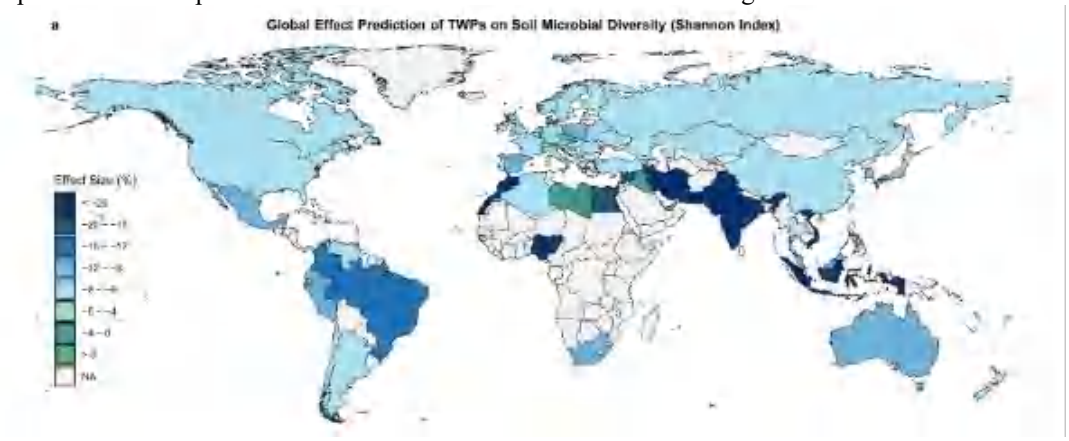



Figure 1. Global effect prediction of TWPs on the soil microbial diversity

# Microplastics disrupt nitrogen-fixing bacterial community with consequences for plant growth

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## ABSTRACT

Microplastic pollution is a global environmental concern in terrestrial ecosystems, yet less is known about microplastic effects on nitrogen-fixing bacterial communities and rhizobia nodulation, the interactions between bacterial communities, nodulation, and soil properties, and how these effects influence plant growth. To address this gap, we conducted a greenhouse experiment using red clover (Trifolium pratense L.) as a phytometer grown in soils amended with microplastic fibres (polyamide, polyester, and polypropylene; 0.4% w/w). At harvest, we assessed soil physicochemical properties, total and nitrogen-fixing bacterial communities, nodulation, root traits, and plant growth. Our results show that the effects of microplastics ranged from positive to negative on these parameters, as a function of polymer type. For example, polyamide and polypropylene impacted positively soil carbon (10.38% and 11.48%, respectively) but negatively specific root length (51.73% and 58.63%, respectively), whereas polyester negatively affected both soil aggregation (17.93%) and nodule number (71.11%). Relative importance analysis revealed that soil nitrogen, root and nodule mass, and the abundance of *Azospirillum* and *Pelobacter* were the strongest predictors of shoot growth. Microplastics further modified the direction and strength of correlations among root, soil, and microbial variables, for instance, most necessarily converting the weak association between shoot mass and *Azospirillum* abundance into a strong positive relationship. These findings reveal that microplastics restructure plant–soil–microbe interactions by altering nitrogen-fixing bacterial communities and nodulation, emphasizing the complex, context-dependent interactions within the plant–soil–microbe system and highlighting the importance of considering microplastic polymer-specific effects when assessing their ecological impact.

**Keywords:** Microplastics; Nitrogen-fixing bacteria; Nodulation; Plant-soil-microbe interactions

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Author, A.B. and Author, C.D., Paper Title, Journal Name, Volume (Year) Page Numbers.

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# Aging of plastic polymers used in agriculture affects sorption of pesticides and their subsequent release

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**ABSTRACT**

In the last decades, modern agriculture has made massive use of plastic based materials that are only in part recovered and in large part dispersed at the soil surface. Exposure to sunlight, during use or after incorrect disposal, causes rapid loss of plasticizers, so that the materials become more brittle and prone to fragmentation, with the consequent production of micro-plastics and their dispersion in soil and water. Photochemical reactions fueled by UV radiation increase this environmentally harmful phenomenon by inducing the breaking of bonds and the incorporation of oxygen with the production of polar functional groups, which modify the surface characteristics of the material.

We hypothesized that these modifications may affect the behavior of micro-plastics towards contaminants and examined the absorption and desorption isotherms of three herbicides, namely Linuron, DNOC and Atrazine on two polymers that are among the most widely employed in agriculture: nylon 66 (PA6) and HDME. The polymers were subjected to artificial aging by exposing them to an UV-light source (254 nm) for ten days. Modification of the polymers'stucture was monitored by ATR FTIR spectrometry and revealed, in both cases, increased presence of oxygen bound C. In particular, HDME displayed an increase at 1720 $cm^{-1}$ (C=O in carbolxyls) and PA6 at 1050 $cm^{-1}$ (C-O stretching).

Sorption isotherms for the new and aged plastics were constructed by measuring UV absorption of 0.2 m filtered solutions at the wavelength of maximum absorbance of each pesticide after either 24h and 8 days of equilibration. The eventual pH changes of the solutions equilibrated with the new and aged plastics and that of the plastics equilibrated with the pesticides were recorded. The observed increase in polarity of aged plastics caused an increase of sorption for all the three pesticides on HDME, whereas on aged PA6, albeit Atrazine sorption increased, those of Linuron and particularly of DNOC were reduced. Desorption isotherms were also obtained for Atrazine and Linuron sorbed on PA6. The percent amount desorbed after 24h or 8 days from aged plastics was larger for both pesticides, but, after 24h desorption, the aged plastics still retained larger amounts (x/m) of pesticides than the corresponding non-aged materials. Linuron and Atrazine have similar log Kow values, namely 2.76 vs. 2.63, but displayed different desorption trends from the same type of polymer. This behaviour is likely to be caused by the lower solubility of Atrazine. This preliminary study shows that aging not only modifies the sorption capacity of pesticides by polymers, but may also affect their desorption. Plastic fragments can retain contaminants for a long time, they therefore can act as carriers to distant ecosystems such as the marine environment and their aging reduces, but does not block the release of sorbed pesticides. This behaviour strongly depends both on the polarity of the material and the solubility of the pesticide.

**Keywords:** Microplastics, pesticides, aging, adsorption,

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# Mineralization and transfer of polymer-derived carbon from biodegradable mulch into the soil microbial biomass and organic matter pool

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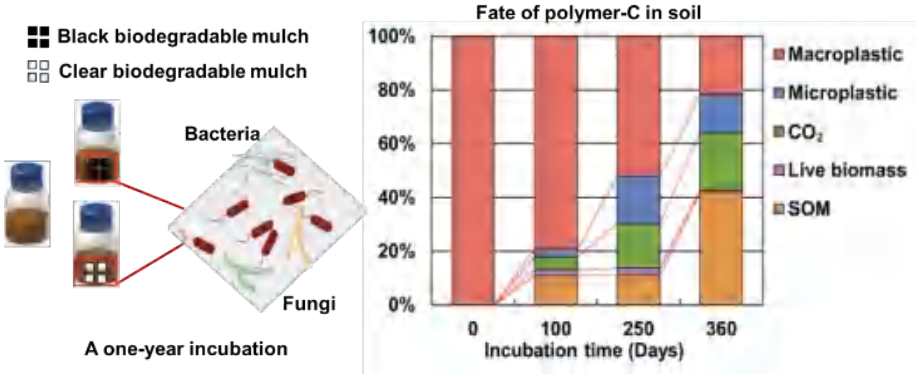
## ABSTRACT

The use of biodegradable mulch (BDM) instead of conventional plastic mulch film has the potential to reduce the accumulation of legacy plastic in agroecosystems. The fate of BDM polymer carbon (C) in soil, however, remains poorly understood, especially the fraction of polymer-C that enters microbial catabolic (mineralization) versus anabolic (immobilization) pathways. We present a novel approach that allows tracking of polymer-C into $CO_2$, macro- and micro-plastic residues, living microbial biomass, and soil organic matter (SOM) through the combination of $CO_2$ emission, $^{13}C$- and $^{14}C$- phospholipid fatty acid (PLFA) analysis, and plastic polymer analysis. After exposing a clear BDM pieces (2 cm × 2 cm) in an agricultural soil for up to one-year, we found that 22 ± 9% (mean and standard deviation) of the polymer-C remained as macroplastic residues (>1 mm), 19 ± 3% was present in microplastic particles (<1 mm), 22 ± 1% was emitted as $CO_2$, 0.9 ± 0.1% was present in living microbial biomass, and 37 ± 9% was present in microbial necromass or SOM. Similar values were observed for black BDM (21 ± 3%, 10 ± 2%, 21 ± 4%, 0.8 ± 0.0%, 47 ± 6%, respectively). Our findings indicate that, within one year of soil incubation, a fraction of the macroscopic BDM pieces fragmented into microplastics, but also a fraction of polymer-C was mineralized and emitted as $CO_2$ and another substantial fraction transferred into SOM. Our research advances knowledge on reducing reliance on polyethylene-based plastics and offers practical implications for improving agroecosystem sustainability.

***Keywords:*** Biodegradation; Carbon cycling; Microbial community; Natural abundance; PLFA.

***Synopsis:*** Our results demonstrate that 37 to 47% of polymer-C in BDM enters into SOM within one year of soil incubation, indicating that long-term use of BDM has short term benefit to improve soil carbon status.

***Graphical ABSTRACT:***



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# Characterization of microplastics using pyr-GC/MS and their leaching and runoff behavior in soil

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**ABSTRACT**

Recent studies on microplastics (MPs) have mainly focused on aquatic environments and organisms, because the complex composition of soils makes it difficult to separate and analyze MPs in soil. Therefore, establishing soil-specific analytical methods is required and this study aimed to separate various types of microplastics (polypropylene; PP, high density polyethylene; HDPE, polystyrene; PS, polyethylene terephthalate; PET) from soils and to analyze using a pyrolyzer-gas chromatography/mass spectrometry (Pyr-GC/MS). Microplastics were separated based on density differences by sequentially applying 40% ethanol, deionized water, 5 M NaCl, and 7.5 M NaI solutions, and recovery of each MPs was evaluated by filtering and weighing MPs with stainless steel (SF) and glass fiber (GF) filters. The combined SF+GF filter showed the highest recovery (101.16%), followed by GF (97.61%) and SF (86.26%). The recoveries were 133.31% for PP, 70.62% for HDPE, 103.48% for PS, and 101.36% for PET. The co-detection of HDPE in PP fraction separated with 40% ethanol suggested that small HDPE particles, having similar density to PP, floated with the 40% ethanol solution. Consequently, a single-density separation using 7.5 M NaI followed by pyr-GC/MS quantification was established as an effective method for determining MPs in soils. Applying this method to agricultural soils revealed that the concentrations of MPs were found to range from 4.28 to 76.8 mg/kg. Furthermore, soil microplastic behavior was assessed through rainfall simulation after spiking soils with 0.05% of each polymer type (PP, HDPE, PS, and PET). Under simulated rainfall of 50 mm/h repeated three times, both leaching and runoff rates were approximately 0.3%. Among the MPs, PS showed the highest leaching rate, whereas the low-density PP exhibited the greatest runoff potential. These results indicate that approximately 99% of the added MPs remained in the soil, suggesting their long-term persistence and possibility posing potential ecological impacts on soil ecosystems and plants.

**Acknowledgments**

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# Assessment of the reliability to extract soil microplastics by a flotation sieving method

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## ABSTRACT

Plastic-based materials have been wildly used for crop production and increasing amounts of plastic waste are deposed in farms. The waste disposal results in the plastics being decomposed and fragmented to form microplastics (MPs) in the field, which are less than 5 mm in size. And then the MPs accumulation in farmland soil would be at risk of food safety and environmental protection. However, it is difficult to precisely measure soil MPs for assessing the impacts of MPs pollution on crop production and human health. The bottlenecks of measuring soil MPs are still on recovering MPs from soil, identifying MPs material, and counting or weighing MPs. There is not a well standardized method to measure soil MPs and delineate MPs distribution in a farm. In the present study, the plastic materials of low-density polyethylene (LDPE) and polypropylene (PP) were used to conduct a recovery test with three farmland soils (i.e. Chaikongtso, Tapaisa, and Pinchen). MPs in the ranges of particle size (i.e. 4–1.7 mm, 1.7–0.149 mm, and 0.149–0.053 mm) were prepared, respectively. Then, 1 g MPs was drawn from every class and added into a pot with 47 g of air-dried soil, thoroughly mixed to prepare a 6% MPs-added soil sample, and further proceeded with three dry–wet cycles to mimic the soil under real field conditions. Next, the MPs-added soil samples were through three rounds of density separation in a 1 L settling cylinder and filtration through sieves of 10, 100, and 270 mesh to separately recover the three particle sizes of MPs. The filtered MPs were oven-dried and then weighed to calculate the recovery. In results, the MPs either LDPE or PP were extracted from the soil by using the floatation sieving method to achieve the average recovery of about 91%. The extractions of MPs in size of the fractions of 4–1.7 mm and 1.7–0.149 mm could be recovered almost 100%; however, in the small size fraction (i.e. 0.149–0.053 mm) the recoveries of MPs extraction were lower and about 60–70%. The settlements in the cylinder bottom were further examined under the optical microscope, and we found the fine particles of MPs aggregated with soil particles. This revealed that the MPs in size of lower 0.149 mm (i.e. to pass through 100 mesh) couldn't float up completely on the top fluid level of soil suspension in the cylinder. Thus, the small size fraction of MPs in soil would be underestimated by using the method to measure. Even though, the sedimentation-based extraction coupled with sieving provided stable recoveries of about 90% for MPs extraction from soil, and this has potential for a preliminary survey of MPs pollution in agricultural soils.

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# National Inventory of Plastic Mulch Residues in Chinese Croplands from 1993 to 2050

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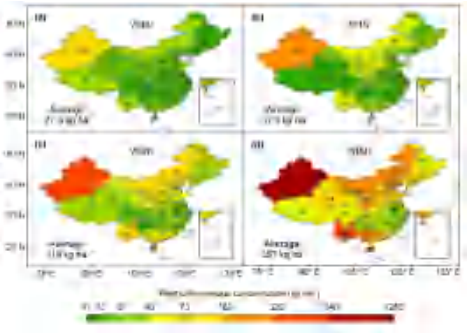
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## ABSTRACT

Agricultural plastic mulch films are a major source of plastic pollution of croplands. In China, which uses about 68% of the plastic mulch film produced globally (ca. 1.4 million tonnes $y^{-1}$), soils have been heavily contaminated with mulch fragments. Here, we collected a national dataset of macroplastic residues (> 5 mm) in soil, including 3145 sampling sites, and provincial plastic film usage from 1992 to 2019 in China, and we established a linear model between the residue amount and historical cumulative usage within each province. Using the model, we quantified the amount of macroplastic residues in Chinese croplands on a national scale during the past 30 years and predict plastic pollution until 2050. Our results reveal the total national amount of plastic mulch residue in 2020 to be 2.07 million tonnes with a 95% CI of [1.67, 2.58]. This accumulated amount of plastic in Chinese soils roughly equals the annual amount of plastic films used globally (2.08 million tonnes in 2018), and is about 8% of national historically used plastic mulch film (27.3 million tonnes) remaining in soil as legacy plastic. Plastic concentrations in Chinese croplands in 2020 range from 7.7 kg $ha^{-1}$ in Anhui to 399 kg $ha^{-1}$ in Xinjiang, with an average value of 119 kg $ha^{-1}$ (equivalent to 0.03 g $kg^{-1}$ soil). We predict that the total amount and average concentration of plastic residues in Chinese croplands will reach 6.24 million tonnes and 357 kg $ha^{-1}$ (equivalent to 0.1 g $kg^{-1}$ soil) in 2050 under current plastic usage. There is an urgent need for regulatory actions to control plastic pollution in Chinese agriculture.

***Keywords:*** Agricultural plastic; Macroplastic pollution; Plastic residues; Plastic film mulch; Sustainable agriculture; Plastic waste.

***Graphical ABSTRACT:***



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# Harnessing Trichoderma spp. to Enhance Foliage Yield and Quality of Lettuce (Lactuca sativa L.) in Microplastic-Contaminated Soils: A Sustainable Strategy for Global Soil Health and Food Security

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## ABSTRACT

Agricultural systems worldwide are increasingly threatened by emerging pollutants, particularly microplastics, which have now been identified as persistent and globally distributed contaminants in terrestrial ecosystems. Modern agriculture extensively relies on plastic-based materials—mulch films, drip irrigation lines, greenhouse covers, compost bags, and nursery trays—whose fragmentation over time results in the accumulation of microplastics (<5 mm) in soils. Among these, low-density polyethylene (LDPE), commonly used in both black and white forms, is the most prevalent due to its chemical stability and slow degradation rate. Microplastics disrupt soil structure, impair microbial diversity, alter nutrient cycling, reduce water retention, restrict root growth, and enhance the mobility of toxic heavy metals, thereby posing significant risks to soil health, crop productivity, and food safety.Given these concerns, the search for environmentally safe, biologically driven mitigation strategies has intensified. Beneficial microbial inoculants—particularly Trichoderma spp.—have emerged as promising solutions due to their ability to promote plant growth, solubilize nutrients, produce organic acids and enzymes, suppress soil-borne pathogens, and enhance plant tolerance to abiotic stress. Recent evidence suggests that Trichoderma may also influence the behavior of contaminants such as microplastics, potentially modifying their mobility, transformation, or stabilization in soil.With this global context, the present study was conducted during the Rabi season of 2024–25 at Banaras Hindu University, India, to evaluate the interactive effects of LDPE microplastics and Trichoderma spp. on soil health and lettuce performance. The objectives were to: (i) examine the effects of black and white LDPE microplastics (2.5% and 5% w/w) on soil physical, chemical, and biological properties; (ii) assess their impact on lettuce growth, biomass, physiology, nutrient uptake, and heavy metal accumulation; (iii) determine whether Trichoderma spp., alone or combined with vermicompost, mitigates the adverse impacts of microplastics; and (iv) evaluate the feasibility of microbial bioremediation as a sustainable approach to improving soil resilience and crop performance in plastic-contaminated environments.A controlled net-house experiment was conducted using sandy clay loam Inceptisol collected from the university research farm. Lettuce (Lactuca sativa L.), a shallow-rooted and pollution-sensitive leafy vegetable, served as the test crop. Nine treatment combinations were formulated, comprising control soil, two concentrations of LDPE microplastics (2.5% and 5% w/w in black and white forms), and their integration with Trichoderma spp. and vermicompost. Soil and plant parameters—including bulk density, porosity, water-holding capacity, organic carbon, available nutrients, dehydrogenase activity (DHA), physiological stress markers (malondialdehyde and proline), chlorophyll content, growth attributes, yield, tissue nutrient content, and heavy metal accumulation—were systematically assessed. ATR-FTIR spectroscopy was used to examine the potential translocation of microplastic particles into lettuce tissues.Microplastic addition significantly impaired soil physical structure. Bulk density increased to 1.13–1.14 Mg $m^{-3}$ under microplastic-only treatments, compared with 1.00–1.05 Mg $m^{-3}$ in Trichoderma-amended soils. Particle density declined to 2.01–2.09 Mg $m^{-3}$ due to the replacement of dense mineral particles by lightweight LDPE fragments. Correspondingly, soil porosity decreased to 45.5–46.2%, and water-holding capacity dropped to 43.7–45.7%, indicating disrupted soil aggregation, reduced aeration, and impaired root-zone moisture dynamics.Microplastics also decreased soil organic carbon (from 0.39% in control to 0.21% in 5% black LDPE and 0.20% in 5% white LDPE treatments), reduced available nitrogen and phosphorus, and suppressed micronutrient availability (Mn, Cu, Fe). Moreover, LDPE contamination enhanced the mobility of toxic heavy metals (Cr, Cd, Ni, Pb), increasing their environmental and food safety risks.Soil biological activity declined sharply: dehydrogenase activity dropped to 88.43 µg TPF $g^{-1}$ $hr^{-1}$ under 5% black LDPE, compared with 108.31 µg TPF $g^{-1}$ $hr^{-1}$ in the control, indicating impaired microbial metabolism. Lettuce grown under these conditions exhibited reduced plant height, leaf number, leaf area (52.2–70.4 $cm^2$), leaf area index (0.07–0.10), and chlorophyll content. Fresh biomass decreased to 118.3–140 g $pot^{-1}$ and dry biomass to 13.7–16.7 g $pot^{-1}$. Elevated levels of malondialdehyde (66.00 nM $g^{-1}$ FW) and proline (2.014 µmol $g^{-1}$ FW) under 5% black LDPE confirmed severe oxidative and osmotic stress. Heavy metal accumulation in lettuce foliage increased, particularly Cr and Pb under 2.5% white LDPE. ATR-FTIR analysis revealed no detectable polyethylene particles in aerial tissues, suggesting anatomical or physiological barriers to microplastic translocation or detection limitations at small particle sizes.Application of Trichoderma spp., particularly when combined with vermicompost, significantly counteracted the adverse effects of microplastics. Soil amended with Trichoderma showed reduced bulk density, improved porosity, enhanced water-holding capacity, and higher organic carbon content. Biological activity improved markedly, as reflected by increased DHA. Trichoderma also moderated heavy metal mobility, likely through biosorption, chelation, and microbial transformation mechanisms.

Lettuce plants treated with Trichoderma and vermicompost exhibited higher plant height, greater leaf expansion, enhanced chlorophyll content, improved root elongation and branching, reduced oxidative and osmotic stress, significantly better nutrient uptake, and superior fresh and dry biomass. These improvements led to substantially higher foliage yield and quality, demonstrating the strong bioameliorative potential of Trichoderma in microplastic-stressed soils.Overall, this study provides clear evidence that microplastic contamination severely disrupts soil health, nutrient dynamics, microbial functioning, and plant physiology. However, Trichoderma spp., particularly when integrated with vermicompost, offers an efficient, low-cost, and eco-friendly strategy to restore soil quality, enhance crop productivity, and reduce heavy metal accumulation in plants grown in microplastic-contaminated soils. The findings contribute to global efforts under the International Union of Soil Sciences (IUSS) toward sustainable soil management, pollution mitigation, and the protection of food quality and ecosystem health

**Keywords:** Trichoderma spp.; Low-density polyethylene (LDPE) microplastics; Lettuce (Lactuca sativa L.); Vermicompost; Dehydrogenase activity (DHA); Oxidative stress; Proline; Malondialdehyde (MDA); Soil microbial activity; Bio-amelioration; Microbial bioremediation; Plastic-polluted soils

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# Revealing Microplastic Contamination in Coastal Soils in Southern Italy via ATR-FTIR and SEM

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## ABSTRACT

Microplastics (MPs), defined as polymer fragments smaller than 5 mm, are currently among the most widespread pollutants. This size range encompasses a highly diverse set of particles, from fragments that are almost visible to sub-micrometre particles. Such variation can complicate both extraction and analysis, given that the physical and chemical behaviour, environmental fate and ecological effects differ markedly within this range. Initially, research on microplastics focused primarily on aquatic environments; however, recent studies have shown that soils can also accumulate substantial amounts of MPs. Their extraction, characterisation, and quantification are challenging due to the heterogeneous nature of soil matrices, and no standardised methodologies are currently established.

This study investigates the presence and typology of microplastics in sandy soils from a coastal area in Molise region (Campomarino), in southern Italy, periodically affected by wildfires. Four sites were sampled: three located in fire-affected areas and one unaffected control site. Multiple extraction methods were employed to isolate MPs. Dry-sieving through 2 mm, 1 mm, and 0.8 mm meshes yielded three fractions, which were initially examined under a Nikon SMZ645 stereomicroscope and subsequently, with an attenuated total reflectance-Fourier transform infrared (FTIR-ATR) for qualitative analysis to identify the MPs samples. The FTIR spectra were compared with an internal standard polymer library. The fraction below 0.8 mm underwent density separation using sodium iodide (NaI), sodium chloride (NaCl), and zinc chloride ($ZnCl_2$), allowing the isolation of particles with lower density than the mineral fraction. Surface morphology was analysed using a SEM-EDS provided high-resolution imaging to observe degradation features, while elemental analysis (EDS) indicated the presence of surface contamination, both organic and mineral (Fig. 1). Approximately 212 particles were extracted from 10 kg of control soil. They were classified by shape as fibres, fragments, films, and spherical particles exhibiting significant surface degradation, rupture or fracture, which was likely caused by physical, chemical and biological degradation. Spectral analysis revealed that the main polymers present are high- and low-density polyethylene (HDPE and LDPE), polyethylene terephthalate (PET) and polypropylene (PP) (Fig. 1).

This study highlights that the identification and quantification of microplastics in complex matrices such as soil require complementary analytical methods. Moreover, the development of standardised protocols is essential to ensure comparability among studies and to achieve a clearer understanding of microplastic pollution.

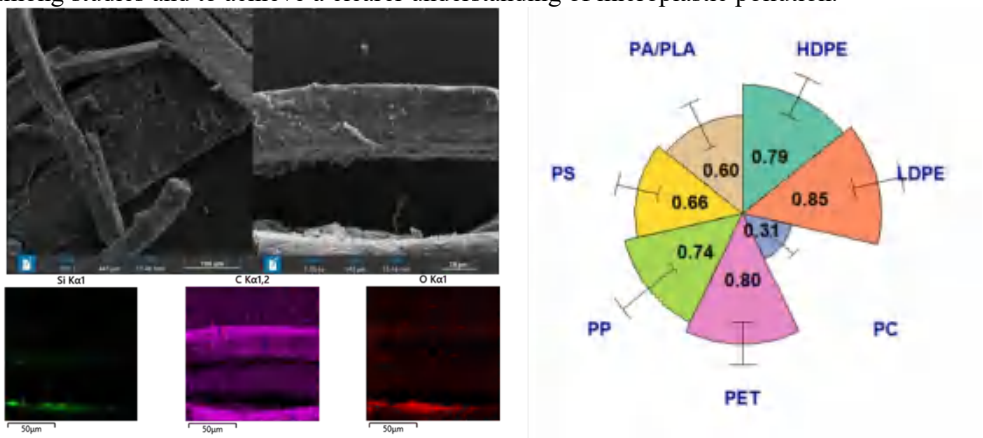



Figure 1. SEM imaging coupled with elemental characterization of a microplastic fragment (left), and relative abundance of the identified polymer classes (right)

# Effects of microplastics on microbial communities and antibiotic resistance genes in the soil-plant system

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**ABSTRACT**

Microplastics (MPs), a growing environmental concern, have attracted widespread attention due to their potential threats to soil health. While the environmental behaviors of conventional and biodegradable microplastics are relatively well studied, their specific impacts on the rhizosphere microbial community and the propagation of antibiotic resistance genes (ARGs) remain insufficiently understood. This study aims to systematically investigate the complex interactions among microplastics, microbes, and ARGs in the soil-plant system.

To accomplish this, a pot experiment with wheat was conducted, involving seven treatments: a control without MPs and groups amended with 0.02%, 0.2%, or 2% (w/w) of either non-biodegradable polystyrene MPs (PS-MPs) or biodegradable poly(butylene adipate-co-terephthalate) MPs (PBAT-MPs). After five months of greenhouse cultivation, the rhizosphere soil was collected for analysis.

Metagenomic sequencing was performed using the Illumina NovaSeq 6000 platform to reveal changes in soil microbial community structure and their association with ARGs. The study found that species diversity increased with higher concentrations of the same type of microplastic. Additionally, specific differences in microbial community composition were observed; for example, the relative abundance of Acidobacteriota decreased significantly in the PBAT 0.2% and 2% treatment groups. Furthermore, PCoA analysis showed varying degrees of separation between the experimental groups and the control group. To gain deeper ecological insights, microbial co-occurrence networks will be constructed. Through this network inference, ARGs will be linked to their potential microbial hosts. Additionally, path analysis will be employed to identify possible pathways through which microplastics may indirectly influence ARG dynamics by altering microbial community structure and soil properties.

This study aims to provide crucial scientific evidence to better understand the ecological effects of both conventional and biodegradable MPs. The findings will help assess the potential risk of MPs acting as vectors for the environmental spread of ARGs. They will offer a solid theoretical foundation and data support for a comprehensive risk assessment of plastic pollution in agricultural ecosystems.

**Keywords:** microplastic pollution; rhizosphere microbial community; antibiotic resistance genes; metagenomic sequencing; soil-plant system

**Acknowledgments**

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# Short-Term Exposure to Polystyrene Micro- and Nanoplastics modifies Soil Nutrient Availability without affecting Lettuce Productivity in Tropical Climate

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## ABSTRACT

Microplastics (MPs) and nanoplastics (NPs) are considered emerging contaminants in terrestrial ecosystems, particularly in agricultural soils. Despite the global concern, their impact on soil properties and crop growth in tropical agroecosystems remains poorly understood. Polystyrene (PS) represents one of the widely used polymers and a major contaminant in soils worldwide. In this study, we investigated the effects of synthesized PS-MPs (5–10 µm) and PS-NPs (100–150 nm) on soil nutrients and lettuce growth. We synthesized PS-MPs and PS-NPs in the laboratory and confirmed their morphology and size by scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR), ensuring chemical identity and surface integrity before use. These particles were incorporated into a tropical Typic Rhodustalf soil at concentrations ranging from typical agricultural contamination to industrial pollution scenarios (0.002–0.2% w/w) in a controlled greenhouse pot experiment with lettuce (*Lactuca sativa*) over 45 days. Soil and plant quality indicators include soil pH, electrical conductivity (EC), available phosphate, ammonium N, nitrate N, and fresh and dry biomass were monitored at harvest. Plant height, chlorophyll content, and leaf number were measured weekly. Factorial ANOVA revealed that PS-MPs and PS-NPs significantly altered soil nutrient dynamics at the highest concentrations, increasing ammonium, nitrate, and available phosphorus, with PS-MPs exerting stronger effects than PS-NPs. Conversely, they had no detectable impact on soil pH, EC, plant growth or biomass during the 45-day exposure period. These results demonstrate a temporal disconnect wherein soil nutrient cycling is disrupted before observable effects on plant development emerge, primarily at contamination levels representing industrial pollution rather than typical agricultural soils. Long-term studies are therefore needed to determine whether sustained exposure at field-relevant concentrations compromises soil fertility and crop productivity in tropical agricultural systems.

**Keywords :** Plastic, Environmental pollution, Tropical soils

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# Determining a Carbon Mass Balance and Active Degraders of Isotopically Labeled Polylactic Acid (PLA) in Soil

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**ABSTRACT**

Biodegradable plastic mulches (BDMs) offer the agronomic advantages of polyethylene (PE) films while, in principle, reducing end-of-season plastic waste. Yet current test methods (e.g., ASTM D5988) quantify only relative $CO_2$ evolution, leaving unknown how much BDM-derived carbon enters non-respired soil pools, or which microbes truly drive degradation. Here, we quantify the fate of BDM-derived carbon in soil and identify its microbial degraders using separately labeled $^{14}C$- and $^{13}C$-labeled poly-L-lactic acid (PLA).

We synthesized $^{14}C$- and $^{13}C$-enriched PLA via azeotropic polycondensation and amended triplicate 100 g agricultural soil microcosms (0.1% w/w PLA), incubated at 25 °C for one year. Continuous NaOH trapping is capturing cumulative $^{14}CO_2$, and at day 365 we will destructively harvest microcosms to partition $^{14}C$ among microbial biomass, dissolved organic carbon, particulate organic matter, mineral-associated soil organic matter (MAOM), and residual polymer, yielding a closed $^{14}C$ mass balance. In parallel, a set of $^{13}C$-PLA microcosms was destructively sampled weekly for eight weeks to capture peak mineralization, and heavy DNA was separated via CsCl density gradients. 16S rRNA amplicon sequencing of heavy versus light DNA identified bacterial taxa actively assimilating PLA-derived carbon.

Preliminary $^{14}CO_2$ data indicate that approximately 5-10% of added PLA-C was respired within the first 60 days. $^{13}C$-qSIP results show enrichment of PLA-C in heavy DNA from *Actinobacteria*, *Proteobacteria*, and *Firmicutes* implicating a specific decomposer guild in both mineralization and stabilization of BDM-derived carbon. This study provides one of the first full soil carbon budgets for BDM-amended soil and explicitly links polymer fate to definite microbial degraders, advancing both sustainability assessment and the mechanistic understanding of polymer–microbe interactions in agricultural soils.

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# Temporal Dynamics of Microplastic Accumulation and Soil Quality under Plastic Mulching in Mediterranean Soils

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**ABSTRACT**

Microplastics (MPs) in soils have attracted increasing scientific attention, yet their implications for soil quality and the role of mulching duration are not fully understood. This study aimed to determine how MP accumulation in mulched agricultural soils affects soil physical, chemical, and biological quality across different mulching durations. Soil samples were collected from two depths (0–10 and 10–20 cm) at 15 agricultural sites in Adana, Türkiye, characterized by a hot-summer Mediterranean (Csa) climate, representing plastic mulching durations of approximately 5, 10, and 30 years. Microplastics were extracted using density separation and identified by ATR-FTIR spectroscopy. Soil quality was evaluated using the Soil Management Assessment Framework (SMAF), integrating physical, chemical, and biological indicators, including bulk density (BD), aggregate stability (AS), available water content (AWC), water-filled pore space (WFPS), soil pH, electrical conductivity (EC), available phosphorus (P), exchangeable potassium (K), soil organic carbon (SOC), microbial biomass carbon (MBC), and potentially mineralizable nitrogen (PMN). Clear differences in MP abundance and soil quality were observed among mulching durations. At the 0-10 cm depth, MP abundances were 69.3 ± 18.2, 64.0 ± 14.39, and 48.0 ± 9.53 particles $kg^{-1}$ for short-, medium-, and long-duration mulching, respectively, whereas at the 10-20 cm depth, MP abundances increased from 37.33 ± 6.18 and 48.0 ± 9.75 to 78.66 ± 27.76 particles $kg^{-1}$ under long-duration mulching. These patterns indicate progressive vertical redistribution of MPs with increasing mulching duration. Prolonged mulching was associated with a 10% increase in bulk density and substantial reductions in aggregate stability (48%), potentially mineralizable nitrogen (24%), and microbial biomass carbon (14%) at the soil surface. Soil physical quality declined most strongly with increasing MP accumulation, while chemical indicators showed moderate, depth-dependent responses. Integration of soil indicators revealed a consistent decline in overall soil quality, with the Soil Quality Index decreasing by approximately 9% under medium duration mulching and 17% under long-duration mulching. These findings demonstrate that continuous plastic mulching leads to cumulative MP redistribution within the soil profile and measurable degradation of soil physical structure, biological functioning, and integrated soil quality. As a field-based study conducted under real agricultural conditions, environmental and management variability should be considered when interpreting the results.

**Keywords** Plastic debris, Soil health indicators, SMAF approach, Pollution

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# Microplastic Quantification in Urban Farmland Soils Using Elutriation: Insights from a Compost-Amended Site

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**ABSTRACT**

Microplastics (MPs) in farmland soils amended with urban compost since 2005 were extracted using an elutriation device adapted from marine sediment protocols (1) for soil application.

MPs were recovered from both the entire soil and from the <2 mm fraction, then quantified (mass and counts) and characterized via FTIR-PAS. Results indicated MP concentrations and particle counts consistent with existing studies (2-7), with polystyrene, polyethylene, and polypropylene as the predominant polymers. Key methodological insights include the necessity of volume-based sampling (5), analyzing the total soil matrix rather than solely the <2 mm fraction (7), and pretreatment for breaking up soil aggregates through ultrasonication or dispersion to enhance elutriation efficiency (2, 4).

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# Effects of microplastics on litter decomposition in Shengjin Lake wetlands

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**ABSTRACT**

Wetlands, as critical transition zones between terrestrial and aquatic ecosystems, play a vital role in regulating the global carbon cycle and maintaining ecosystem services. Despite the increasing accumulation of microplastics (MPs) in wetland soils, their impacts on litter decomposition remain insufficiently understood. This study aims to systematically investigate the effects of MPs pollution on wetland litter decomposition characteristics and their driving factors.

To accomplish this, we focused on litter from dominant vegetation in the hydro-fluctuating zone in Shengjin Lake wetland. We conducted a 100-day indoor mesocosm pot experiment and a 6-month field in situ burial experiment was conducted. Ten treatments were established: a control without MPs and groups amended with 0.1%, 0.5%, or 2.5% (w/w) of polyethylene MPs (PEMPs), polyvinyl chloride MPs (PVCMPs), or polystyrene MPs (PSMPs).

The results indicated that: (1) Under laboratory conditions, MPs inhibited litter decomposition primarily by elevating the litter carbon-to-nitrogen (C:N) ratio and suppressing enzyme activities. High concentrations of PVCMPs significantly suppressed decomposition by reducing microbial diversity. In contrast, the addition of 2.5% PEMPs strongly inhibited decomposition at the early stage; however, decomposition gradually recovered at later stages, coinciding with fungal community succession toward *Mortierellomycota* and the upregulation of genes involved in chitin degradation. (2) Field experiments further demonstrated that MPs compromised soil structural stability. High concentrations of PVCMPs and PSMPs significantly reduced the contribution of soil fauna to litter decomposition to 11.49% and 16.71%, respectively, whereas soil fauna exhibited partial tolerance to low concentrations of PEMPs.

Overall, this study provides key scientific evidence regarding the processes and potential mechanisms by which MPs affect litter decomposition. The findings are of great significance for unraveling wetland carbon cycling processes, protecting wetland ecosystem services, and developing strategies for pollution control of MPs.

**Keywords:** Microplastics; Wetland ecosystem; Litter decomposition; Soil microbial communities; Soil enzymatic activities

**Acknowledgments**

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# Screening of microplastic-degrading bacteria and their effect on lettuce growth under pollution stress

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**ABSTRACT**

Microplastics (MPs) have accumulated in farmland soils, posing a potential threat to crop safety and human health. Microbial degradation represents a highly promising remediation strategy; however, it currently faces challenges such as limited resources of functional strains and unclear mechanisms of their effects on crop growth. To address these gaps, this study aims to achieve two core objectives: (1) To screen for functional strains capable of efficiently degrading polyethylene microplastics (PEMPs) and polypropylene microplastics (PPMPs) from environmental samples. (2) To investigate the alleviating effects and underlying mechanisms of the PEMPs-degrading strains on lettuce growth under PEMPs-induced stress.

To enrich and screen functional strains, selective media with MPs as the sole carbon source were employed. Single colonies were isolated and purified via dilution plating and streak plating, followed by strain identification using 16S rDNA sequencing. Subsequently, the strains were inoculated into mineral salt media containing either PEMPs or PPMPs as the sole carbon source.Their microplastic-degrading capabilities were validated by determining the weight loss rates of MPs, along with observing morphological changes using scanning electron microscopy (SEM) and analyzing structural changes via Fourier transform infrared spectroscopy (FTIR). A strain, *Bacillus tropicus* SQF-1, was isolated from activated sludge. This strain achieved a PEMPs weight loss rate of up to 0.971% over a 35-day incubation period.

Furthermore, the strain *Bacillus tropicus* SQF-1 was introduced into lettuce cultivation systems supplemented with PEMPs at a concentration gradient of (0.1%, 1%, 10%). The results showed that PEMPs inhibited lettuce seed germination and seedling biomass accumulation; at high doses, they also impaired chlorophyll synthesis. However, inoculation with *Bacillus tropicus* SQF-1 effectively mitigated PEMPs-induced stress, promoted seedling growth, and significantly enhanced the richness and diversity of the rhizosphere microbial community.

The findings not only expand the resources of microplastic-degrading microbial strains, but also provide theoretical underpinnings and data support for the development of microbial remediation strategies to mitigate microplastic contamination in agricultural soils.

**Keywords:**Microplastic pollution; Microplastic-degrading bacteria; Agricultural soil; Lettuce; *Bacillus tropicus* SQF-1

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The research was supported by the National Natural Science Foundation of China (42207459), the Anhui Provincial Natural Science Foundation (2208085QC69).

# Earthworms Mediated Fate of Microplastics in Soil

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**ABSTRACT**

Plastics are widely used in agricultural production worldwide, and the release of plastic additives and debris has attracted increasing attention. Bio-based and/or biodegradable plastics (BPs) have been actively promoted in the market, however, their environmental fate in soil remains unclear, leaving doubts over their overall impacts to the global plastic pollution. Earthworms (EWs) can process significant amounts of soil and associated materials, the activities of which greatly impact soil fertility and structure. The encounters of microplastics (MPs) and EWs in soil are inevitable, if MPs, especially those derived from the uncontrolled disposal of BPs, are to enter and accumulate in soils. Therefore, the role of EWs in altering the properties and environmental behavior of MPs cannot be ignored.

Here, the fate of MPs during the soil-gut-cast transit mediated by EWs was explored. First, the fate of MPs during the ingestion and digestion processes of EWs was studied at mesocosm scale, where EWs were incubated for 49 days in soil spiked with 1% (w/w) MPs. Then, we studied the fate of MPs during the cast aging process after excretion at microcosm scale, where fresh casts (containing MPs) were left aging for 180 days. Low-density polyethylene (LDPE), polylactic acid (PLA), and polybutylene adipate terephthalate (PBAT) were used as model polymers, and *Lumbricus terrestris* was selected as the model species. The changes in the particle size distribution (PSD), concentration, and chemical composition of MPs were studied. The concentrations of PLA and PBAT MPs in the microcosm experiment were quantified by two methods: density separation with gravimetric analysis (DS) and Soxhlet extraction with q-NMR (SE).

Results showed that MPs could be fragmented and depolymerized by EWs, and that cast aging had a dual effect on MPs: immobilization and enhanced degradation. However, these effects were polymer type dependent. It was observed that all MPs were fragmented in EW gizzards in the mesocosm experiment but a secondary fragmentation during cast aging only occurred for PLA and PBAT. Evident depolymerization was found only for PLA in the gut (17.7% reduction in molar mass), but the concentrations did not change during gut passage, indicating that the short gut transit time only initiated a low level of depolymerization. The concentration, PSD, and chemical composition of LDPE MPs did not change during cast aging. The concentration of PBAT MPs in casts by DS decreased sharply with increasing aging, while the data by SE suggested no reduction. Such divergent trends indicated that cast aging caused immobilization of MPs, making MPs less available for the aqueous extraction. Interestingly, both methods confirmed that PLA concentration decreased significantly during cast aging (30–40% reduction) but not during soil incubation. In summary, our research indicates that EWs play an important role in regulating the fate of MPs in soil, and the underlying mechanisms require further investigation.

**Acknowledgments**

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# Long-term Field Evidence on Microplastic Generation and Altered Soil Functioning by Biodegradable Film Mulch

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## ABSTRACT

The adoption of biodegradable plastics such as poly (butylene adipate-co-terephthalate) (PBAT) in agriculture is promoted as a sustainable alternative to conventional polyethylene (PE) mulch. However, concerns persist regarding their incomplete degradation into microplastics (MPs) and the subsequent effects on soil biogeochemical cycles and microbial ecosystems, posing a new “hidden pollution” from a presumed solution. This study systematically conducted a long-term (15-year PE + 8-year PBAT) field application to evaluate MP accumulation, polymer transformation, and their cascading impacts on soil carbon dynamics and microbial community structure.

Results showed that total MP abundance was higher in the PBAT plot (15-year PE + 8-year PBAT, 8507 ± 578 particles/kg) than that in a plot with 23 years of continuous PE use (6767 ± 336 particles/kg). The PBAT plot was enriched with finer MPs (<0.25 mm) and unique film-shaped fragments identified as polyester-terephthalate and polyester, tere-&iso-phthalate, which are intermediate degradation products of PBAT. Source apportionment indicated that ~57% of MPs originated from historical PE use, while ~33% derived from PBAT. While soil organic carbon (SOC) was higher in the PBAT plot (30 g C/kg) compared to the PE plot (27 g C/kg), the labile carbon pools directly associated with microbial vitality were significantly suppressed. Specifically, dissolved organic carbon and microbial biomass carbon measured only 74 mg C/kg and 246 mg C/kg in the PBAT plot, respectively, contrasting with 120 mg C/kg and 413 mg C/kg in the PE plot. Stable isotope ($\delta^{13}C$) analysis showed contrasting carbon flows: in PBAT soil, carbon shifted from micro-aggregates (<0.25 mm) to macro-aggregates (>0.25 mm), whereas in PE soil, carbon moved primarily between macro-aggregates, indicating altered carbon stabilization mechanisms.

Microbial community analysis revealed that both the PE plot and the PBAT plot significantly reduced bacterial Chao1 richness, Shannon diversity, and niche width compared to the no-mulch (NM) control. The PBAT plot exerted the strongest selective pressure, yielding the lowest diversity metrics. It consistently enriched fast-growing, copiotrophic bacterial taxa such as *Proteobacteria* (particularly *Alphaproteobacteria*) and *Bacteroidetes*, while depleting oligotrophic groups like *Acidobacteriota* and *Chloroflexi*. Despite reduced taxonomic diversity, co-occurrence network analysis demonstrated that the PBAT plot fostered a more connected and robust microbial network with higher average degree and lower modularity, indicating enhanced functional integration and cross-kingdom (bacterial-fungal) synergy, though with increased potential fragility due to reliance on keystone taxa.

This research provides a comprehensive, field-based investigation into the terrestrial fate and effects of MPs from biodegradable agricultural inputs. It contributes to understanding MP sources, transformation pathways, and their ecotoxicological effects on soil health by linking MP accumulation to suppressed microbial activity, altered carbon sequestration pathways, and reconfigured ecological networks. The findings highlight the limitations of equating "biodegradability" with environmental safety based solely on fragmentation or visual disappearance. A truly sustainable solution requires evaluating plastics across their full life cycle, assessing their complete mineralization pathways and their long-term impacts on soil ecosystem function and stability. This study directly supports the session's goal of fostering interdisciplinary exchange to assess and mitigate the environmental risks of MPs in terrestrial ecosystems.

**Keywords:** Biodegradable plastics film, PBAT, Microplastics, Carbon sequestration, Soil microbial community, Long-term field experiment

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# Ecological risk and machine learning prediction of microplastic pollution in peatlands

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**ABSTRACT**

This study investigates the ecological risk of microplastics (MPs) in peatland areas of Long An Province, located in Vietnam's Mekong Delta. Among the thirty sediment samples analyzed, polyvinyl chloride (60.7%), polyethylene (25.8%), and polypropylene (11.9%) were identified as the most abundant polymer types. The hazard index (HI) indicated a Level III contamination risk in Tan Thanh and Thanh Hoa districts. Both the pollution load index (PLI) and the potential ecological risk index (RI) revealed relatively high MP contamination across the studied sites. Based on PLI values, MP levels in the peatlands of Tan Thanh and Thanh Hoa were classified as high and moderate, respectively, while Duc Hue exhibited lower contamination. Overall ecological risk remained concerning, with PLI_overall at Level III, HI_overall at Level V, and RI_overall indicating extreme danger. Also, three machine learning models, Least Squares Support Vector Machines (LS-SVM), Random Forest (RF), and Long Short-Term Memory (LSTM) were trained and tested to predict composite MP quantities using physicochemical parameters and sediment characteristics as predictors. Model outputs showed that MP abundance and characteristics (e.g., color and shape) were strongly influenced by pH, total organic carbon (TOC), and salinity. All three predictive models demonstrated high accuracy on the testing dataset. These findings provide the first quantitative assessment of MP-related ecological risks in peatland ecosystems of the Mekong Delta and highlight the potential of using basic physicochemical variables to predict MP pollution in peatland sediments and other sensitive environments.

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# Changes in the dispersivity of soil substrates after contamination with microplastic polystyrene

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**ABSTRACT**

The dispersivity of soil is a crucial characteristic that significantly determines all other soil properties and regimes. The widespread presence of microplastics (MP) in the environment poses a risk of significant alterations in the physicochemical properties of soil (Guo et al., 2024; Feng et al., 2012).

Polystyrene (PS), one of the most prevalent types of MPs found in agroecosystems, has the potential to impact the water-physical characteristics of soil (Shafea et al., 2023). These changes ultimately affect the structure of the soil and the availability of water for plants. Scientific literature suggests that PS MPs may reduce water permeability, modify pore distribution, and enhance water-repellant properties (Botyanská et al., 2022). The mechanisms of adsorption of MP in soil constituents include surface adsorption, electrostatic interactions, and hydrophobic interactions, which influence the distribution of contaminants and the mobility of elements within the soil profile. The aim of this study is to investigate the transformation of specific surface area and grain size distribution of soil substrates that have been contaminated with PS MPs.

(1) The particle size distribution was determined using laser diffraction analysis on a Malvern Mastersizer 3000E instrument with ultrasonic preparation, at an energy level of 450 J/mL and a processing time of 5 min 20 sec.

(2) Isotherms of water adsorption were obtained using the adsorption-equilibrium method, and (3) Nitrogen adsorption isotherms were measured using the low-temperature, static, volumetric technique on a 3P Sorptometer Vapor 100 automated sorption instrument (3P Instruments, Germany). The test soil comprised Terra Vita soil (NORD Pulp, Russia), mixed with sand at a volume ratio of 2:1. PS aqueous suspension, represented by particles with a diameter of 160 nm, were used to contaminate the soils with MPs. An alteration in the distribution of size fractions of the granulometric composition of the substrate was observed, indicating aggregation upon addition of a PS solution, which is supported by SEM analysis.

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Nitrogen specific surface area was determined by means of the “Analytical complex for determination of texture characteristics of dispersed systems” (Vapor 100, 3P Instruments, Germany, 2021), purchased within the framework of the Development Programme of the Lomonosov Moscow State University.

SEM studies were carried out at the Shared Research Facility “Electron microscopy in life sciences” at Moscow State University (Unique Equipment “Three-dimensional electron microscopy and spectroscopy”).

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# Impact of Microplastic Pollution in U.K. Woodland Soil: Evidence from a Long-Term Soil Burial Experiment

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**ABSTRACT**

Research on microplastics has focused heavily on aquatic environments, leaving a gap in understanding their sources and effects in terrestrial ecosystems. Woodlands, which are vital for biodiversity and many ecological functions, are particularly understudied. One overlooked source of microplastic pollution is woodland management materials such as tree guards, cable ties and outdoor clothing. This research aims to address this gap through an investigation into the impacts of microplastics derived from woodland management materials on woodland soils in the United Kingdom. To do this, a 15-month burial experiment is being conducted to assess how microplastic source, concentration, polymer type, size, and shape influences soil chemistry, microbial activity, and microbial biomass. In addition, the effects of prolonged soil exposure on the physical and chemical properties of the microplastics are being explored using Fourier Infrared Transform Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM). The findings will be shared with woodland management organisations. This communication with key stakeholders in woodland management aims to raise awareness of microplastics as a potential pollutant in woodland ecosystems to support the development of evidence-based policies and sustainable material use in woodlands.

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# Quantification of Micro- and Nanoplastics in Agricultural Soil and Application in Japan

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**ABSTRACT**

Quantification of microplastics (MPs) and nanoplastics (NPs) in soils has been increasingly attempted. However, MPs are generally quantified by particle counting using micro-FTIR or micro-Raman spectroscopy, while NPs are quantified using pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS), making it difficult to assess their abundance on a comparable basis. In addition, existing NPs extraction methods often rely on interactions with soil organic matter, resulting in limited applicability across different soil types. In this study, we explored a unified Py-GC/MS-based workflow that enables mass-based quantification of MPs and NPs, incorporating salt-induced aggregation and subsequent organic matter decomposition for NPs. We then applied this framework to the individual quantification of MNPs in agricultural soils.

Spike-and-recovery tests were conducted for three types of soils—washed quartz sand, a Fluvisol with 3.3% total carbon, and an Andosol with 11.3% total carbon—to evaluate quantification methods for MNPs. MPs were extracted by density separation. As low-density MPs, polyethylene particles (PE-MPs; particle size 150–180 µm, density 1.0 g/cm³) were spiked into soil samples, while polyvinyl chloride particles (PVC-MPs; particle size 106–250 µm, density 1.4 g/cm³) were used as high-density MPs. First, soil organic matter was decomposed using Fenton's reagent. Then, density separation was performed three times with NaI solution (density 1.6 g/cm³), and the supernatants were filtered to recover MPs onto glass filters. For the recovery test of NPs, polystyrene particles (PS-NPs; particle size 101–140 nm) were used. After spiking the NPs into soils, the samples were shaken with TMAH solution to release NPs from mineral particles. The mixture was centrifuged, and the supernatant was filtered through a glass filter. The filtrate was amended with nitric acid and sodium chloride to induce NP aggregation, followed by centrifugation and organic matter decomposition. The filters with MPs and the resulting NP suspension were separately analyzed by Py-GC/MS.

In the recovery experiments for MPs, PE-MPs showed high recovery rates of 81.2–99.7%, regardless of soil type. In contrast, the recovery rate of PVC-MPs decreased to 33.1% after organic matter decomposition. For NPs, 97.8% of PS-NPs were successfully separated from soils using TMAH solution, demonstrating its potential applicability. In addition, the amount of NPs remaining in the soil residue after TMAH treatment was only 1.4% of the added amount, confirming that the TMAH-based extraction effectively separated NPs from the soil matrix. However, the final recovery of NPs from the same Fluvisol showed substantial variability among replicates. This may be associated with insufficient dispersion of recovered NPs, and further methodological improvement is required.

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# Microplastic Contamination in Soil around the Aral Sea in Uzbekistan

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**ABSTRACT**

Plastics are widely used due to their low manufacturing costs and ease of processing; however, microplastics (MPs; <5 mm) have increasingly accumulated in terrestrial and aquatic environment, becoming a global environmental concern. For decades, Uzbekistan's Syr Darya and Amu Darya rivers transported domestic wastewater and irrigation water into the Aral Sea. Since the 1960s, excessive water withdrawal has caused the Aral Sea to shrink, may have promoted microplastic accumulation in both surface water and exposed dried soils. In arid regions, strong ultraviolet radiation, low soil organic matter, and soil crust formation may further influence the environmental behavior of microplastics. However, information on soil microplastics contamination in Uzbekistan remains extremely limited. This study provides a preliminary assessment of the abundance, color, shape, and polymer composition of microplastics in Aral Sea surface water and surrounding dried soils. Soil samples were collected from dried lakebed areas at multiple depths to evaluate vertical distribution and potential migration of microplastics. Surface water samples were obtained from the Aral Sea. To minimize contamination, samples were stored in aluminum containers and processed under controlled conditions. After sieving, particles larger than 1 mm were removed by visual inspection. Microplastics were extracted using density fractionation with sodium iodide (NaI) as a heavy liquid and identified using Fourier-transform infrared (FTIR) spectroscopy (Katsumi et al., 2022). For particles with ambiguous spectral features, additional characterization was conducted using gas chromatography–mass spectrometry (GC–MS). Microplastics were detected in both the Aral Sea water and the surrounding soils of our research sites and indicating widespread contamination across aquatic and terrestrial environment. This study provides baseline data on microplastic contamination in Aral Sea region and contributes to understanding potential sources and environmental behavior of microplastics in Central Asia.

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# Characterization of Small Microplastics in Japanese Agricultural Soils and Their Effects on Soil Aggregate Structure

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**ABSTRACT**

Microplastics (MPs) have been suggested to disrupt soil structure and degrade soil functions; however, the occurrence and impacts of small microplastics below 100 µm remain poorly understood. Small MPs are expected to interact strongly with soil particles and organic matter; however, their effects on soil structure have not been sufficiently clarified. In Japan, information on MP contamination in agricultural soils is still limited, and knowledge of their impacts in volcanic ash soils is especially limited. In this study, agricultural soils from Tokyo, Chiba, Ibaraki, and Okinawa were investigated to characterize MP contamination using a modified separation method capable of isolating plastic particles in the 20–100 µm size range (Katsumi et al., 2022). After separation, the size, color, shape, and polymer type of individual microplastic items were recorded. In addition, MP addition experiments were conducted to evaluate the effects of small MPs on soil aggregate structure.

Across all study sites, microplastic items smaller than 100 µm were consistently abundant, and a wide range of polymers not used as agricultural materials was detected. In particular, farms located near urban areas showed higher numbers of microplastic items and a greater proportion of fibrous MPs. These results suggest non-agricultural sources of microplastics in the studied soils. Micro-FTIR analysis identified numerous items that were difficult to distinguish from plant residues. Subsequent verification using pyrolysis GC-MS demonstrated that many of these items were not plastics, indicating that reliance on micro-FTIR alone may lead to overestimation of small MP abundance. Furthermore, MP addition experiments indicated that film-shaped MPs of approximately 200 µm can inhibit the formation of coarse soil aggregates larger than 2 mm.

Overall, these results suggest the widespread presence of small microplastics in Japanese agricultural soils, highlight methodological challenges in quantifying MPs below 100 µm, and indicate potential impacts of small MPs on soil aggregate structure.

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# Oxidized Residues Accelerate Phosphorus Immobilization via Enhanced Surface-induced Nucleation

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**ABSTRACT**

The accumulation of plastic residues (PRs) and their oxidized counterparts (OPRs) in agricultural soils poses a potential influence on phosphorus (P) geochemical cycling and availability. Bioavailable P can be immobilized through its transformation into insoluble calcium phosphates (CaPs). The influence of PRs and OPRs on CaPs formation remains poorly understood. To address this issue, we selected polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), along with their oxidized counterparts, as representative PRs. The In situ atomic force microscopy revealed that OPRs significantly accelerated the nucleation of CaPs at the solid-solution interface. In addition, real-time confocal Raman microscopy and high-resolution transmission electron microscopy (HRTEM) showed that OPRs promoted the phase transition from amorphous calcium phosphates (ACP) to hydroxyapatite (HAP), a highly insoluble and bio-unavailable form. These changes indicate that OPRs further reduce P bioavailability in soils. This effect is attributed to enhanced binding between CaP nuclei and PR surfaces following oxidation, which lowers the interfacial free energy and reduces the energy barrier for CaPs nucleation and crystallization. Our findings reveal a previously unrecognized mechanism by which OPRs exacerbate P-immobilization in soils, emphasizing the urgent need to address plastic pollution and improve P-management in PR-contaminated agricultural systems.

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# Ten years of microplastics in the soil-plant system research-what have I learned?

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**ABSTRACT**

Microplastics (MPs) are commonly defined as plastic particles with diameter smaller than 5 mm from one of two sources: intentionally fabricated primary MPs and unintentionally degraded secondary MPs originating from larger plastic items. With this definition, it is easy to note that MPs are not a new material at all. Rather, the term represents a categorization of small plastic particles based on a specific size threshold.

The ecological risk of plastic waste was recognized by pioneering marine researchers as early as in the 1960s. However, the upsurge of interest in MPs began in 2004, following a paper in *Science* that formally introduced the term 'microplastics' to refer to 'microscopic plastic debris'. Recognition of MPs in soil came even later; it was not until 2012 that Matthias C. Rillig first called for research on MPs in terrestrial ecosystems. To my knowledge, I conducted the first experimental investigation on the effects of MPs on plant growth in 2016, which was subsequently published in a peer-reviewed journal in 2018. Inspired by the review paper in *Science* by Richard C. Thompson et al. in 2025, which reviewed current understanding and future prospects of MPs pollution research from 2004 to 2024, it is pertinent to summarize the research about MPs in the soil-plant system from 2016 to 2026.

The soil-plant system encompasses numerous processes, which can be categorized as physical, chemical, and biological. For the past decade, my research has consistently focused on the key scientific question: how the interaction between MPs and soil microorganisms affects soil ecological functions. The deeper I delve into my research, the more strongly I recognize the need to contextualize my findings within the big picture. A comprehensive understanding of MPs in the soil-plant system calls for collective efforts among soil scientists, botanists, microbiologists, ecologists, and agronomists, given that these processes are intricately linked.

In my view, a framework for systematic analysis and synthesis of soil-plant systems is useful to identify, study and elucidate the most important processes, which may even help predict the evolutionary trend of MPs pollution. Ultimately, all the related research could not only fill our knowledge gaps, but also contribute to the greater good of society.

**Keywords:** microplastics; soil-plant system; microorganisms; soil ecological functions

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# Uptake Process and Toxicity Mechanism of Microplastics and Phthalate Esters in Plant

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**ABSTRACT**

The extensive use of plastic mulch in agriculture has led to the accumulation of micro-nanoplastics (MNPs) and phthalate esters (PAEs) in soil-plant systems, posing potential threats to human health and ecosystems. Using lettuce as a model crop, this study systematically investigated plant uptake and transport of sub-microplastics (SMPs) and their associated physiological and molecular responses. Furthermore, it revealed the combined effects of co-contamination with a typical PAE—di(2-ethylhexyl) phthalate (DEHP)—and SMPs in soil-plant systems. By employing techniques such as fluorescence labeling, scanning electron microscopy, confocal laser scanning microscopy, transcriptomics, and metabolomics, this research clarified the uptake pathways, physiological toxicity, and molecular mechanisms of SMPs in lettuce, particularly under co-exposure with DEHP. The results demonstrated that: first, SMPs could be absorbed by lettuce roots and translocated to leaves, leading to downregulation of ion homeostasis-related genes, activation of the antioxidant system, and enhancement of sphingolipid metabolism. Second, compared with negatively charged SMPs, positively charged SMPs more readily entered leaves through stomata and the cuticle, causing stronger physiological toxicity and greater regulation of gene expression, particularly upregulation of circadian rhythm-related genes. Notably, in the soil-plant system, DEHP did not exhibit synergistic toxicity with SMPs. Instead, DEHP inhibited the accumulation of SMPs in plants, alleviated MP-induced oxidative stress and metabolic disorders, and mitigated the negative impact on soil bacterial community diversity. This indicates a complex antagonistic interaction between SMPs and PAEs. This study provides physiological and molecular evidence for understanding the multidimensional impacts of agricultural plastic pollution and offers a scientific basis for developing risk management strategies.

**Key Words:** micro-nanoplastics, phthalate esters, plant, soil, environmental behavior

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# Development of a protocol for the extraction and quantification of nanoplastics in agricultural soils

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**ABSTRACT**

Agricultural soils are important sinks for plastic debris, with macro- and microplastic contamination widely reported, whereas nanoplastic (NP) remain poorly documented. Their nanoscale size, strong interactions with soil constituents, and the limited sensitivity of current analytical techniques make reliable extraction and quantification of NPs challenging. Therefore, improved and thoroughly validated methods are urgently needed to understand the occurrence, behavior, and fate of NPs in soils.

This study is among the first to develop an extraction and quantification protocol for nanoplastics, including polyethylene (PE, 68 nm), polypropylene (PP, 56 nm), polymethyl methacrylate (PMMA, 219 nm), polyvinyl chloride (PVC, 404 nm), and europium-doped polystyrene nanoparticles (Eu-PS, 198 nm), from three different References LUFA soil types (loamy sand, clay loam, and silty clay). The extraction protocol comprises dispersion using tetrasodium pyrophosphate, followed by organic matter digestion with hydrogen peroxide and nanofiltration, and subsequent identification and quantification using single-particle inductively coupled plasma mass spectrometry (sp-ICP-MS) and pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS). Sp-ICP-MS enabled highly sensitive detection of the Eu-PS tracer, allowing accurate quantification of extraction recovery at each stage of the protocol. Py-GC/MS was used for overall recovery assessment by identifying and quantifying all spiked polymer types based on their characteristic pyrolysis products.

Preliminary results showed that soil type affected Eu-PS NP extraction recovery. The highest recoveries were obtained from loamy sand, followed by clay loam and silty clay, for both particle number concentration (73–80%, 56–60%, and 49–50%) and mass concentration (63–72%, 52–60%, and 46–49%). spICP-MS analysis showed that Eu mass per particle remained consistent across all samples, indicating no substantial leaching or aggregation of the metal tracer. Therefore, the extraction procedure likely did not alter particle integrity. Ongoing Py-GC/MS measurements are being conducted to further assess polymer-specific recovery.

This study serves as a stepping stone for analytical method development for nanoplastics in soils and contributes to understanding how polymer type and soil properties influence extraction efficiency, supporting improved assessment of the environmental occurrence and fate of nanoplastics.

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# Chemical and biochemical approaches to assess the biodegradation of polyhydroxyalkanoates in soil

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## ABSTRACT

Fossil-derived plastics represent a global concern, due to their negative effects on the environment, such as their persistent accumulation in soils and water bodies, and their noxious bioactivity on various organisms (1). Therefore, innovative and environmentally friendly polymers have been proposed, such as polyhydroxyalkanoates (PHAs), microbial polyesters produced to store carbon and energy (2). However, despite their synthesis meet the current sustainability criteria, the knowledge about their degradation in soils and their effect on soil biochemistry is limited, especially when added in presence of vermicompost (VC). This substrate is indeed known to stimulate the activity of soil microbial community and may therefore affect PHAs degradation (3). Our work aimed at investigating the biodegradation of PHAs materials in soil, to establish a relationship between the degradation process and the soil characteristics.

The PHAs studied were synthesised by solvent casting, using 400 mg of either Polyhydroxybutyrate (PHB) (PHB-400) or the copolymer poly(3-hydroxybutyrate-co-3- hydroxyhexanoate) (PHBHHx) (COP-400). Also, 200 mg of PHB (PHB-200) were used to study how the amount of polymer casted affects its degradation. Each material was placed in *non*-degradable pouches, buried in a sandy soil added or not with VC, and kept at 25 °C under a water regime of 45% WHC. At specific time points, bioplastics were recovered and their weight loss was measured. Also, their morphological and thermal properties was evaluated via Scanning Electron Microscopy (SEM) and Differential Scanning Calorimetry (DSC). Moreover, the activity of *β*-glucosidase and acid phosphatase were assessed in the soil.

The fastest degradation occurred for COP-400, due to its amorphous nature, which made it more accessible to microorganisms, whereas PHB-400 was more resistant to biodegradation agents. Besides, a faster degradation was noted for PHB-200 compared to PHB-400, likely due to its higher surface area-to-volume ratio, which enhanced its contact with the biodegradation agents. Despite VC addition did not affect significantly the polymer weight loss, its qualitative effect on biodegradation was evident through SEM images and DSC of the dug materials. The effects of biodegradation were also reflected in soil biochemical activities, as evidenced by an increase in *β*-glucosidase activity, related to the addition of the polymeric carbon-based substrate, and a decrease in acid phosphatase enzymatic activity.

Future studies focusing on the microbial communities developed in the soil during the biodegradation, or testing different amount of biopolymer added, could provide valuable insights into the degradation events, then advancing our understanding of the degradation process and its impacts.

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# Soil metabolome impacts the formation of the eco-corona and adsorption processes on microplastic surfaces

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**ABSTRACT**

The Eco-corona on microplastics refers to the initial layer of biomolecular compounds adsorbed to the surface after environmental exposure. The formation and composition of the eco-corona in soils has attracted relatively little attention; however, this has important implications on the fate and impacts of microplastics, and their associated chemical additives, in the terrestrial environment. To this end, black polyethylene film microplastics, white polyethylene film microplastics and pure polyethylene microplastic granules were selected as typical polyethylene (PE) microplastic, which is one of the most abundant microplastics in soil. Three types of soil, including mollisol soil, fluvo-aquic soil, and red soil, were collected to obtain different soil metabolomes. Both the non-targeted and targeted metabolomics, along with several spectroscopic techniques, were used to test the formation of eco-corona on microplastics based on soil metabolites. The sorption of dibutyl phthalate (DBP) as a proxy for a soil contaminant on the microplastics with or without eco-corona was investigated. Here we demonstrate a fast formation of eco-corona on polyethylene microplastics exposed to water-extractable soil metabolites (WESMs) via two pathways: direct adsorption of metabolites on microplastics and bridging interactions mediated by macromolecules. The main eco-corona components were identified as lipids and lipid-like molecules, phenylpropanoids and polyketides, nucleosides, nucleotides and their analogues. The WESMs were found to reduce sorption of organic contaminants on microplastics by two pathways: reduced adsorption to the eco-corona surface and co-solubilization in the surrounding water. The impact of eco-corona formation should be considered an integral part of environmental fate and risk assessments of terrestrial emissions of microplastics and associated contaminants.

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# Changes in Soil Biological Activity Induced by Increasing Doses of Aged Microplastics in Agricultural Soil

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**ABSTRACT**

Microplastic (MP) pollution presents potential negative effects on microbial communities and soil biogeochemistry; however, results are still contradictory. This variability increases when considering the different types of polymers that make up plastics, such as degradable and non-degradable ones, and the use of pristine MP in studies, which do not represent the actual state of these contaminants in nature. In this context, this study aims to evaluate the effect of two types of MPs, polylactic acid (PLA) and low-density polyethylene (LDPE), at different contents and degradation levels, on the biological activity of agricultural soil. LDPE and PLA were mechanically ground and sieved to obtain particles smaller than 5 mm. Subsequently, they were irradiated with 600W solar simulation lamps for one month, with a 12-hour photoperiod and periodic agitation, verifying their degradation status with FT-IR-ATR at 0, 15, and 45 days. This resulted in aged and pristine LDPE and PLA, which were applied at 0.25%, 2.5%, and 5% w/w to an agricultural soil, establishing a mesocosm experiment for 12 weeks. At the end, the following soil biological parameters were analyzed: fluorescein diacetate (FDA) hydrolysis, dehydrogenase activity (DHA), acid phosphatase (Pacid), urease (UA), arylsulfatase (ARY), and respiration induced with alpha-cyclodextrin (CLYC). Also, sequencing of the 16S rRNA and ITS genes was performed to analyze alpha and beta diversity of microbial communities. A potential prediction of microbiota functionality for bacteria and fungi was also conducted using FAPROTAX and FungalTraits, respectively. Results show that DHA activity decreased by up to 70% solely due to PLA across all doses and degradation states. Conversely, Pacid increased threefold under PP and aged PLA. FDA and UA showed no significant treatment effects. CLYC activity decreased linearly with increasing aged LDPE, with no differences among other treatments. Bacterial richness and evenness increased under 5% aged LDPE, showing a similar trend for PLA but with a clear decrease at the lowest dose (0.25%). Fungal communities showed a decrease in richness for all PLA treatments, and only for aged LDPE at 5%. This resulted in microbial community structure discrimination by dose and degradation state for both bacteria and fungi, including an effect of plastic type only for fungi. Functional prediction revealed a potential increase in pathways associated with cellulolysis, aromatic hydrocarbon degradation, denitrification, etc., due to 5% aged LDPE and PLA. Thus, the PLA presence exerts negative effects on catabolic activity but positive effects on certain microbial hydrolysis processes. In summary, the effects of MP on soil microbial communities depend on the dose: low concentrations decrease diversity due to competition for colonization surfaces, while high concentrations increase microbial richness and evenness by providing more niches. H. Aponte thanks to FONDECYT "Iniciación" 11241285.

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# Effects of secondary microplastics input on the mineralization of soil organic carbon

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**ABSTRACT**

Different types of secondary microplastics are widely present in the soil. This study investigated the effects of secondary microplastics (MPs) on soil organic carbon mineralization in two distinct soil types: red soil and saline soil. Using pristine, photoaged, and pyrolyzed PVC MPs at concentrations of 0.5% and 5%, incubation experiments were conducted to monitor $CO_2$ and $CH_4$ emissions, soil pH, carbon components, enzyme activities, dissolved organic matter (DOM), and microbial community structure. Results showed that secondary MPs, especially pyrolyzed MPs, significantly enhanced cumulative $CO_2$ and $CH_4$ emissions compared to pristine MPs and controls. Pyrolyzed MPs had a greater impact on $CO_2$ emissions in red soil and on $CH_4$ emissions in saline soil. MPs addition decreased pH in red soil but increased it in saline soil, promoting oxidation and reduction reactions, respectively. Soil organic carbon and dissolved organic carbon increased in both soils, along with elevated β-glucosidase activity. Microbial diversity increased in red soil, with a notable rise in Acidobacteriota, while saline soil exhibited greater fungal community shifts. The findings indicate that secondary MPs accelerate soil carbon mineralization by altering soil properties, enzyme activities, and microbial communities, with pyrolyzed MPs exhibiting the most pronounced effects.

**Acknowledgments**

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# Interfacial Colloidal Behavior of Microplastic-Pollutant Complexes and Its Regulation by Environmental Conditions

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**ABSTRACT**

The environmental behavior of microplastics (MPs) is governed by their interfacial colloidal dynamics, which are complicated by co-existing pollutants. This study systematically investigates how organic pollutants (ionic/non-ionic) modulate the colloidal stability of MP composites under varying environmental conditions.

Key findings reveal that pollutant type and interaction mode critically control stability. Ionic pollutants can either stabilize or destabilize MPs depending on charge compatibility, while non-ionic pollutants generally enhance stability in solution but promote aggregation upon adsorption. pH and cation type ($Na^+$ vs. $Ca^{2+}$) further interact with adsorbed pollutant layers, leading to non-DLVO behaviors—such as charge shielding, bridging, and hydration layer alteration—that traditional models cannot predict. Natural macromolecules like humic acid (HA) and bovine serum albumin (BSA) differentially affect stability: HA enhances stability in $Na^+$ but promotes $Ca^{2+}$-bridging, whereas BSA provides stronger steric stabilization across both ionic environments.

This work advances the mechanistic understanding of MP-pollutant co-transport in complex aqueous systems, offering critical insights for environmental risk prediction.

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# Soil microplastic risk from microcosms to field surveys: nematode bioindicators across scales from individuals to micro-food webs

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**ABSTRACT**

Terrestrial microplastic (MP) ecotoxicology is still dominated by liquid/agar tests and single model species, limiting environmental realism and comparability. We integrated soil-based microcosms with field monitoring to identify risks from individuals, trophic interaction and micro-food web level. A conventional MPs of low-density polyethylene (LDPE) and a biodegradable MP blend of poly(lactic acid) (PLA) and poly(butylene adipate-co-terephthalate) (PBAT) were evaluated. We aim to answer four questions: 1) Determine how plastic characteristics, soil texture, and environmentally relevant aging (microbial vs. photo-oxidative) modulate LDPE and PLA/PBAT impacts on nematode *C. elegans* performance, including offspring output, growth, and fertility. 2) Compare nematode species sensitivity to LDPE and PLA/PBAT using behavioral endpoints—locomotion, foraging activity, and food selection—in common soil nematodes. 3) Quantify MP-induced shifts in soil micro-food-web structure and functioning, emphasizing nematode–microbe trophic links and changes in energy flux under LDPE and PLA/PBAT exposure. 4) Examine how MPs interact with co-occurring environmental drivers to influence microbial biomass and community composition in Yangtze River bank soils and river sediments. We found that 1) Individual nematode fitness could be influenced mainly by soil type, plastic amount and aging (Zhang et al., 2025a). 2) MPs exposure could result in nematode behavioral disorders in moving, foraging and food choice (Zhang and Ruess, 2025). 3) MP could alter food web by negatively changing nematode and microbial biomass and structure, activity and energy flux. 4) MPs could interact with other human-sourced pollutants such as antibiotics and metals to reshape microbial community (Zhang et al., 2025b). Overall, MP effects in soils are context dependent and can scale from nematode fitness/behavior to shifts in nematode–microbe interactions and micro-food-web functioning. Linking soil microcosms with Yangtze River field monitoring strengthens risk assessment by involving co-occurring pollutants.

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# Before You Measure: How Sampling Strategies Shape Microplastics Quantification in Soils

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## ABSTRACT

Microplastics (MPs) in soils exhibit strong spatial heterogeneity driven by land use, source proximity and soil processes. The rapid pace at which terrestrial MPs research has developed outpaced the development of robust, standardized procedures along the entire analytical workflow, including sampling strategies. Without representative sampling, uncertainty introduced at the earliest stage of the analytical chain propagates through extraction, analysis and interpretation. As a result, many reported MPs distributions, including quantification, characterization and risk assessments, remain challenging to interpret, difficult to compare and lack reproducibility.

Here, we present a multi-step sampling framework designed to improve the accuracy, precision and comparability of MPs quantification in soils. Using laboratory-scale model systems representing different MPs contamination scenarios, we systematically evaluated the effects of different sampling strategies on sample representativeness (Figure 1). To enable high-throughput assessment, we used model metal-doped MPs synthesized in-house, where the metals acted as conservative tracers and were quantified by ICP-MS, circumventing the need for more lengthy traditional MPs analysis. We demonstrate that producing a representative analytical aliquot is highly dependent on the preceding homogenization and mass-reduction techniques. Post-homogenization, subsequent aliquots from experimental systems exhibited high sample-to-sample variability indicating incomplete homogenization (Figure 2). Representativeness is strongly dependent on MPs morphology (fragments vs. fibers), since fibers are likely entangled in soil and harder to homogenize. Amongst mass reduction techniques, riffle splitting was most effective, though when used alone was insufficient to ensure sample representativeness (Figure 3). This is likely due to de-mixing phenomena and segregation of the homogenized bulk, often unconsidered in sampling workflows.

While we used a specific soil and MPs combination here, these findings emphasize the need to pre-test sampling approaches, using References materials to identify and account for segregation heterogeneity and other de-mixing phenomena in the given sampling conditions. Ongoing work extends this framework to larger, more environmentally realistic systems to develop a reproducible framework for MPs sampling across different soil environments. Overall, this work provides a workflow for representative MPs sampling in soils and identifies critical bottlenecks that must be addressed to support harmonized monitoring and inter-study comparability.

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# Synthesis of Hierarchical Porous Magnetic Zeolite-Biochar Composites from Solid Waste for Micro/Nanoplastics Adsorption in Soil-Groundwater Systems

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## ABSTRACT

The widespread distribution of micro/nanoplastics (MNPs) in the environment poses potential threats to ecological safety and human health. To achieve low-consumption and high-efficiency removal of MNPs, this study developed magnetic hierarchical porous adsorbents using geopolymer precursors and sawdust solid waste via a reduction roasting-hydrothermal method for nanoplastics removal from water. Optimal synthesis conditions were determined as: alkali-thermal roasting at n(Na:Al:Si) = 3.2:1:1, 20% sawdust incorporation, 700°C for 2 h, followed by hydrothermal treatment at n(Na:water) = 3.2:1, 100°C for 12 h. These conditions yielded magnetic A-type zeolite-biochar hierarchical porous materials with pore sizes ranging from 1 to 110 nm. During this process, aluminosilicates (e.g., quartz, kaolinite, nepheline) in the raw materials were activated into sodium silicate and sodium aluminate, eventually forming A-type zeolite. Simultaneously, sawdust pyrolyzed into biochar, and hematite in red mud was reduced by biochar to zero-valent iron, imparting magnetic properties. The as-prepared materials exhibited high adsorption capacity for nanoplastics and excellent reusability, with facile recovery under an external magnetic field. A maximum adsorption capacity of 125.5 mg/g was achieved for polyethylene (PE) nanoplastics. Adsorption behavior varied significantly with the surface charge and natural organic matter modification of the nanoplastics. The primary adsorption mechanisms involved hydrophobic interactions, electrostatic attraction, and hydrogen bonding. Dynamic column experiments further validated the material's removal capability in simulated soil systems. Overall, this hierarchical porous material integrates low energy consumption, high capacity, rapid kinetics, reusability, and magnetic recoverability, demonstrating significant potential for micro/nanoplastics remediation in soil-groundwater treatment systems.

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# How does plastic pollution influence soils and soil fungal communities in temperate alluvial forests

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**ABSTRACT**

Plastic pollution has become a major environmental problem, while the products of its degradation, microplastics (MP), appear everywhere on Earth. Data on MP in primarily agricultural soils are piling in recent years, but there is a significant knowledge gap in forest soils. In Serbia, forests are often the dumping sites for municipal waste, which creates environmental problems that have been rarely documented. In alluvial plains of the three largest rivers in Serbia (Morava, Sava, and Danube), we detected locations with waste depositions and visibly plastic-non-contaminated sites within similar forest/soil types to evaluate MP in topsoil. To explore the influence of environmental factors on soil MP, samples were taken in two years, in three forest vegetational seasons. The impact of MP on soil structure, chemistry, and fungal communities was examined. Large aggregate formation, soil coarse sand content, specific mass, porosity, and available P were the parameters that were strongly affected by contamination. MP was present in all samples, but few times larger amounts were extracted from the visibly polluted soils. Geographical location and environmental factors significantly influenced the behavior of MP in forest soils. Biodiversity and the structure of soil fungal communities were influenced by pollution, as well as by location and environmental factors. Saprotrophs were the most abundant fungal guild (29%), followed by plant pathogens (6%), parasites (4.7%), and mycorrhizal species (4.6%), but only saprotrophs and pathogens were significantly affected by the pollution. All fungal guild members were significantly affected by microplastic content, $P_2O_5$, $K_2O$, CEC, and coarse sand. We conclude that the influence of plastic pollution on fungal communities in temperate alluvial forest soils depends on soil characteristics as well as on seasonal changes in the soil environment.

**Acknowledgments**

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# Insights into the vertical transport of microplastics in agricultural soil: impact of soil pore networks

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**ABSTRACT**

Agricultural soils have become significant sinks for nano and microplastics (NMPs), raising widespread concern regarding their potential threats to soil health and crop safety. This study investigated the transport behavior of two commonly occurring NMPs with different polymeric properties—polyethylene (PE) and polylactic acid (PLA)—in agricultural soils. The results demonstrated distinct transport mechanisms of PE and PLA microplastics within soil pore networks. PE microplastics exhibited greater transport depths, reaching deep soil layers (8–10 cm) during a single infiltration event, whereas PLA microplastics showed significantly limited transport, predominantly distributed within the surface and middle soil layers (0–5 cm). Pore structure heterogeneity, including pore volume, connectivity, and pore-throat constriction, was identified as a critical factor governing microplastic transport. The transport and spatial distribution of PE microplastics were regulated by multiple soil pore parameters: V3D, A3D, L3D, W3D, D3D, EqD, SF, φe, φA, Macro, and Meso significantly promoted PE transport, while θ, φ, Micro, and Nano exerted inhibitory effects. Similarly, the transport of PLA microplastics was influenced by several pore parameters; V3D, A3D, D3D, SF, φe, and φA significantly enhanced the transport of 0.5 μm PLA microplastics, whereas φ inhibited their transport. For 5 μm PLA microplastics, φ was the only parameter that significantly suppressed transport, while no other pore parameters showed significant correlations. Random forest modeling further revealed that V3D, D3D, φe, and Nano were the key soil pore structural parameters controlling the transport of 0.5 μm PE microplastics, whereas φ was identified as the dominant parameter regulating PLA microplastic transport.

**Keywords:** Microplastics, Pore-scale, X-ray computed tomography (XCT), Agricultural soil, Transport patterns

# Nanotoxicomics: Cellular-subcellular Impact of Nanoparticles in Plants

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**ABSTRACT**

The toxicity of nanoparticles (NPs) is concerning issue; especially its effects on plants cellular-subcellular organelles, biochemical and molecular traits. In recent years; nanotechnology has resulted in the widespread use of engineered NPs across various industries, from agriculture to medicine, raising concerns about their environmental and biological impacts. Therefore, the nanotoxicomics are in trending to undertand impact of NPs at various types of plants, different climatic conditions and in soil types. We have conducted series of research experiments in various modules; i.e., hydroponic, model and field experiment, testing different forms, types and sizes of NPs behaviour in the plant tissues as well as its bio-geo-transformation, and long-term impact. Our research results indicate that the plant growth indices were severely affected at high content of NPs in soil hydroponic conditions by affecting the germination rate, root (relative root length by 35%) and shoot lengths (relative shoot length by 10%), accumulation in plant tissues (by 5.7 in roots and 6.4-folds in leaves), maximal quantum yield of photosystem II, and transpiration rate, effects on stomatal aperture and root morphology, metaxylem size and changes in cellular organelles (plastids, mitochondria), as well as in plastoglobules, starch granules, protoplasm, membranes and nucleus. Low molecular weight antioxidants like restored glutathione and ascorbate have been found to increase the activity of glutathione peroxidase (GPX), glutathione-S-transferase (GSTs), and ascorbate peroxidase (APX) in plant tissues, whereas catalase (CAT) activity increased from by 50-70%. The observed disturbance in redox balance signals the upregulation of corresponding genes. Antioxidant enzyme isoform gene transcripts increased for CAT2, and APX under NPs stress. The gene transcription of the subunits of the mitochondria electron transport chain (ETC) changed mainly only under the influence of high concentration of NPs. Expression of the ATPase subunit gene, atp1, increased slightly (by 36 %) in leaf tissue under the influence of medium and high concentrations of NPs, whereas in the root tissues, the atp1 mRNA level decreased significantly (1.6-2.9 times). The formation of electron-dense materials was noted in the intercellular space of cells of NPs-treated plants. This indicates the accumulation of NPs in edible part of crops and raising concern on human health. The mechanistic insights into NPs uptake, including their entry into plant cells, interactions with organelles and biomolecules, and the generation of reactive oxygen species are crucial. This mechanistic understanding of properties of NPs (size, shape, surface charge, and concentration) and plant-specific factors (species and growth stage) significantly influence genotoxic outcomes and can be modulate for efficient input of NPs in sustainable way.

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# Biological Strategy for Identification and Elimination of Organic Pollutants in Agro-Environments

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**ABSTRACT**

1) Identification of organic pollutants in soil. This study aimed to establish a biosensor method for detecting extractable tetracyclines in soils using whole-cell biosensors containing a reporter plasmid (pMTGFP or pMTmCherry) carrying fluorescent protein genes tightly controlled by tetracyclines-responsive control region (tetRO). This whole-cell biosensor method can simultaneously measure 96 or more samples within 6 h and is easily parallelizable, whereas a typical high-performance liquid chromatography (HPLC) method may require 7 times more of analysis time and much greater cost to achieve similar analytical throughput. The biosensor method had a detection limit for each of six tetracyclines between 5.32-10.2 μg/kg soil, which is considered adequate for detecting tetracyclines in ethylenediaminetetraacetic acid (EDTA) extracts of soils. Relative standard deviation was between 19.8%-51.2% for the biosensor Escherichia coli DH5α/pMTGFP and 2.98%-25.8% for E. coli DH5α/pMTmCherry, respectively. This new, fast, easily parallelizable, and cost-effective biosensor method has the potential for measuring extractable concentrations of tetracyclines for a large number of soil samples in large-scale monitoring studies.

2) Elimination of organic pollutants in plants. This investigation provides a novel method of endophyte-aided removal of polycyclic aromatic hydrocarbons (PAHs) from plant bodies. A phenanthrene-degrading endophytic bacterium Pseudomonas sp. Ph6 was isolated from clover (*Trifolium pratense* L.) grown in a PAH-contaminated site. After being marked with the GFP gene, the colonization and distribution of strain Ph6-gfp was directly visualized in plant roots, stems, and leaves for the first time. After ryegrass (*Lolium multiflorum* Lam.) roots inoculation, strain Ph6-gfp actively and internally colonized plant roots and transferred vertically to the shoots. Ph6-gfp had a natural capacity to cope with phenanthrene in vitro and in planta. Ph6-gfp degraded 81.1% of phenanthrene in a culture solution within 15 days. The inoculation of plants with Ph6-gfp reduced the risks associated with plant phenanthrene contamination. Our results will have important ramifications in the assessment of the environmental risks of PAHs and in finding ways to circumvent plant PAH contamination.

3) Elimination of organic pollutants in soil. Engineering natural microbiomes for biotechnological applications remains challenging, as metabolic interactions within microbiomes are largely unknown, and practical principles and tools for microbiome engineering are still lacking. Here, we present a combinatory top-down and bottom-up framework to engineer natural microbiomes for the construction of functionenhanced synthetic microbiomes. We show that application of herbicide and herbicide-degrader inoculation drives a convergent succession of different natural microbiomes toward functional microbiomes (e.g., enhanced bioremediation of herbicide-contaminated soils). We develop a metabolic modeling pipeline, SuperCC, that can be used to document metabolic interactions within microbiomes and to simulate the performances of different microbiomes. Using SuperCC, we construct bioremediation-enhanced synthetic microbiomes based on 18 keystone species identified from natural microbiomes. Our results highlight the importance of metabolic interactions in shaping microbiome functions and provide practical guidance for engineering natural microbiomes

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# Boron in Soil: Linking Microbial Responses and Plant Performance

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**ABSTRACT**

Water scarcity in Mediterranean and arid regions is driving the adoption of desalinated seawater (DSW) as an irrigation source, yet its elevated boron (B) content raises environmental and agronomic concerns. Across a series of complementary studies using soils from southeastern Spain and diverse plant models (ryegrass, tomato, onion, lemon, and apricot), we evaluated how increasing B concentrations and the use of organic amendments affect the soil–plant–microbiome system. Results consistently demonstrated that irrigation with B-enriched or DSW causes B accumulation in soil and plant tissues, modifies soil nitrogen dynamics, and alters the activity, biomass, and structure of soil microbial communities. A threshold around 1 mg B $L^{-1}$ in irrigation water emerged as critical: below this level, soil microbial functionality and crop performance were generally maintained, whereas higher concentrations induced negative effects on microbial respiration, enzyme activities, and community composition—particularly reducing fungal diversity. The magnitude and direction of microbial responses depended on both the B chemical form and the crop species, with more tolerant crops such as tomato or apricot showing limited physiological stress compared with sensitive species like onion and lemon. Organic amendments modified B mobility and bioavailability through interactions with dissolved C and N pools, sometimes enhancing plant B uptake and aggravating toxicity symptoms, despite stimulating microbial biomass. In lemon soils, the combination of DSW and organic inputs intensified B accumulation and impaired photosynthetic performance, while in apricot systems microbial biomass increased without detectable physiological stress. Collectively, these studies reveal that B exerts complex, dose-dependent effects on plant physiology and the soil microbiome, mediated by species sensitivity, soil organic matter, and irrigation water quality. Sustainable use of DSW for irrigation therefore requires careful monitoring of B concentrations, crop-specific tolerance thresholds, and soil organic management to prevent long-term degradation of soil fertility and ecosystem functioning.

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# Chemical characterization, fluorescence properties, and photochemical reactivity of natural dissolved organic matter

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**ABSTRACT**

Dissolved organic matter plays a very important role in aqueous systems, including most notably: *(i)* the carbon cycle, with important implications for the $CO_2$ budget of water environments; *(ii)* the absorption of sunlight, with the ability to protect living organisms from the harmful effects of UV-B radiation, and *(iii)* the production of reactive transient species that are involved in the degradation of xenobiotics and of natural organic compounds.

Several tools can be used to characterize natural organic matter. NMR spectroscopy has allowed important discoveries about the structure of soil humic substances. Further advances were obtained more recently by use of LC-MS and of GC-MS, the latter requiring chemical modification of the sample. All these techniques, to which FT-IR can also be added, are extremely useful but require extensive sample pre-treatment and concentration, in soil extracts and *a fortiori* in the case of natural waters. For this reason, the characterization of organic matter in surface waters is most frequently carried out by use of spectroscopic techniques, namely UV-vis absorption and fluorescence spectroscopy that require virtually no sample pre-treatment. Although limited to the chromophoric fraction of dissolved organic matter (the so-called CDOM), these techniques can provide important insights into its origin and valuable information concerning structure and photochemical reactivity.

This keynote presentation will also deal with the results of recent studies into the possible fluorophores that could account for the fluorescence properties of organic matter, with the double role of the latter as both inducer (photosensitiser) and quencher (reductant) in the photodegradation of contaminants, and with the photomineralisation kinetics on a global scale.

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# Enhanced Sorption of Per- and Polyfluoroalkyl Substances by Soils from Water via Cation Bridging Interaction

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## ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a diverse group of widespread contaminants, and their many environmental impacts are governed mainly by sorption by soils. PFAS sorption is affected by the salts present in soil and water, and the sorption could be enhanced by strengthening cation-bridging interaction between PFAS and multivalent cations on soil surfaces. In this study, sorption experiments of a series of PFAS were conducted to evaluate the effects of PFAS structures on cation-bridging interaction, including (1) hydrophilic head groups (carboxylic vs. sulfonic, e.g., PFNA and PFOS), (2) different electric charges (anionic vs. neutral, e.g., PFOS, PFOSA, and N-EtFOSA), and (3) perfluorinated chain length (e.g., PFHxA, PFOA, PFNA, PFDA, PFUnA, PFDoA, and PFTrA). To quantify the contribution of cation-bridging interaction to sorption, sorption isotherms by soil from water were measured for the soils with cation exchange sites occupied by either $K^+$ or $Ca^{2+}$ with KCl or $CaCl_2$ as background solution. All measured sorption isotherms demonstrated linear relationship between sorbed concentration vs. the aqueous concentration. The obtained distribution coefficients ($K_d$), as the slope of sorption isotherm, increased exponentially with the PFAS C-F chain length. The $K_d$ values of PFAS sorption by Ca-soil was approximately 9 to 17 times greater than that by K-soil. With the same C-F chain length, PFOS with sulfonic acid head group exhibited stronger interaction with soil than PFNA with carboxylic acid group. Sorption of anionic PFAS by Ca-soil was consistently greater than that by K-soil. Neutral PFAS showed no apparent difference in sorption by K- vs Ca-soil, indicating that neutral PFAS chemicals cannot form cation-bridging interaction that anionic PFAS interact with $Ca^{2+}$ through forming specific interaction with cations on soil surfaces. This study provides strong evidence to support the contribution of cation-bridging interaction to PFAS sorption, and offers new insights into the contribution of this mechanism to PFAS retention by soils.

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# ENVIRONMENTAL RISK OF GEOACCUMULATION AND TRANSMISSION OF HEAVY METALS IN TAILING DAMS WITH RADIOACTIVE ELEMENTS

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**ABSTRACT**

The special attention and widespread concern caused by the presence of heavy metals in the environment are mainly due to their physicochemical properties, high toxicity and persistence, and negative effects on biological properties and soil structure, and the possibility of transfer to the human body through agricultural products. Heavy metals in soil can cause respiratory, cardiovascular, and renal diseases. Currently, more than 200 million tonnes of waste have accumulated in 13 tailings ponds in northern Tajikistan, including about 55 million tonnes of uranium waste in 10 tailings ponds. The total area of the tailings ponds is 200 hectares. It should be noted that the tailings are located in the basin of the transboundary Syr Darya River, which, along with the rest of Tajikistan, is an earthquake-prone area with a high frequency of debris flows. The tailings ponds at Taboshar have been subject to repeated erosion by mudslides throughout their existence. The industrial site at Taboshar contains rock dumps with excessive amounts of radionuclides, and the tailings contain radioactive waste from the primary hydrometallurgical processing of uranium ores.

The aim of the present work is a comprehensive assessment of heavy metal content in the soils of radioactive dumps in northern Tajikistan by determining environmental pollution indices and their transfer to plants.

Soil sampling was carried out in accordance with GOST 17.4.3.01-83 of the Interstate Standard for Nature Protection. Soils. General requirements for sampling. The method of soil keys was used for soil sampling of the investigated area. Each key of the study area consisted of five sampling points. Soil samples were taken from a depth of 10-30 cm. The soil samples were dried, crushed, and sieved through a 1 mm mesh sieve. The content of heavy metals was determined by X-ray fluorescence analysis in a Spectroscan MAKS-G spectrometer. The sampling of plants was carried out in the summer seasons of 2023 and 2024.

To study the processes of heavy metal migration and transport in plants, the dominant genus of perennial meadow grasses of the Alopecúrus family was used in the study area. Several methodological tools and complex indicators have been developed to assess the degree of soil contamination with heavy metals. Geoaccumulation index, accumulation coefficient, individual pollution index (PI), general pollution index (PLI), Nemerow pollution index (NPI), and potential ecological risk indicator (RI) allow the identification of areas according to the degree of soil contamination with heavy metals. They are also important for the development of measures to neutralize the effects of heavy metals, for the integrated assessment of soil quality and for predicting the sustainability of ecosystems for crop production under conditions of certain soil contamination with heavy metals.

The soil of the Taboshar tailings dump area belongs to different classes according to the values of the individual pollution index (PI) of heavy metals (Sr, Pb, As, Zn, Cu, Ni, Co, Cr, and V). According to the classification, the soil is considered unpolluted at values PI<1, 1<PI<2 - weak pollution, 2< PI<3 - medium, 3<PI<5 - strong, PI>5 - very strong pollution. The contents of Sr, Pb, Ni, Co, Cr, and V are in the range of 0.13 - 0.77, and according to these elements, the soil of the territory belongs to the class of unpolluted. According to the Zn, Cu content, the soil belongs to the slightly polluted class, and according to the As content, to the highly polluted class.

The values of geoaccumulation index of heavy metals Sr, Pb, As, Zn, Cu, Ni, Co, Cr, and V in the soils of Taboshar dump, from which it can be seen that the scatter of values of geoaccumulation index of metals is in a wide range and for Sr, Ni, Co, Cr and V have a negative value. According to the values of geoaccumulation index of heavy metals, as stated in soils are divided into the following classes: clean (Igeo<0), polluted from weak to medium (0<Igeo<1) from medium to strong medium degree of pollution (1 <Igeo<2). Then medium to heavily polluted (2<Igeo<3), heavily polluted (3<Igeo<4), heavily to very heavily polluted (4<Igeo<5), and very heavily polluted (5<Igeo).

Comparing the result of the heavy metal geoaccumulation index values with the above soil class values shows that the soil of the Taboshar tailings dump area corresponds to the weak to moderate contamination class for Sr, Pb, Ni, Co, Cr, and V. The Zn and Cu values are medium, and As values are from medium to high levels of contamination.

The ratio of the difference between the individual pollution index and the load index to the individual metal pollution index has positive value only for As, Zn, Cu and almost zero value for Pb and negative value for Sr, Ni, Co, Cr and V. This is an evidence that As, Zn and Cu predominate in the soils of Taboshar tailings dump area and among them As has the highest concentration.

On the way of transfer of chemical elements into the human body, and the main link in the biochemical cycle of substances are plants, which are characterised by high absorption capacity. Heavy metals, with their physical and chemical properties, toxicity, and high migration stability, cause widespread concern in terms of transfer to living organisms. This problem has become particularly relevant in recent years due to the increasing anthropogenic pollution of ecosystem components. The study of the migration and transfer of heavy metals into living organisms and the establishment of their regularities are important from a practical point of view for the development of methods of protection against their ingress into crops and further along the 'soil-plant-living organism' chain. In addition, plants can serve as indicators of a heavy metal-contaminated environment.

The Ecological Risk Index (RI) values for Sr, Pb, As, Zn, Cu, Co, Cr, and V of the soil from the Taboshar tailings area show that they are all well below 90, with an average RI value of 59.48 for the whole sampling area. Consequently, the soil of the Taboshar tailings area, namely the soil of the sampling area, is characterised by a low ecological risk indicator for the listed metals.

Thus, as a result of the conducted research, it is established that the contents of Sr, Pb, Ni, Co, Cr, and V are in the interval 0.13 - 0.77, and according to these elements, the soil of the area belongs to the class of unpolluted soils. According to Zn and Cu content, the soil belongs to the class of slightly polluted, and As to the class of heavily polluted soils. The values of the index of geoaccumulation of heavy metals Sr, Pb, As, Zn, Cu, Ni, Co, Cr, and V in the soil of the Taboshar dump are in a wide range, and for Sr, Ni, Co, Cr, and V have a negative value. The soils of the Taboshar tailings area belong to the class of weak to medium contamination in terms of Sr, Pb, Ni, Co, Cr, and V. Zn and Cu values are medium, and As values are from medium to strong contamination. The values of the biological absorption coefficients of Cu, Ni, and Cr are lower, and for the rest, more than 1. Heavy metals with a biological absorption coefficient greater than one are accumulated in plants, while metals with a biological absorption coefficient less than one are taken up by plants.

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# Bioremediation of soil contaminated with boron by using biochar and barley plants

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**ABSTRACT**

Soil is an essential and finite resource, and its degradation through different processes threatens its ecological functions, as well as the sustainable development of agricultural activity. In particular, in agricultural areas characterized by intensive production of irrigated crops under arid and semi-arid climate, the use of desalinated seawater results in the accumulation of boron (B) in soil and crops. Soil bioremediation technologies have emerged as a viable approach to promote the transition from conventional, intensive agrosystems to more sustainable ecological production systems. Moreover, the reuse of processed organic wastes as soil amendments has been proposed as a key strategy for the restoration of degraded soils. Biochar can act as a beneficial organic soil amendment while serving as a catalyst in the bioremediation of contaminated soils, enhancing the B adsorption, and stimulating the activity, biomass and diversity of soil microbial community. In addition, barley plants exhibit a high tolerance to B toxicity and may help mitigate its detrimental effects on soil microorganisms. This study aims to evaluate, at the laboratory scale, the bioremediation of a B-contaminated agricultural soil by integrating the application of two types of organic amendments - a common biochar (BC) and this biochar enriched with a compost (BCE) - with the cultivation of barley plants. Specifically, the study investigates the capacity of biochar, both alone and in combination with compost to reduce the B concentration in the soil solution. Furthermore, it examines whether the proposed bioremediation strategy enhances soil health and quality by assessing several soil enzyme activities, as well as the biomass and composition of the microbial community, in both B-contaminated and uncontaminated control soils. Overall, after 30 days of incubation, we observed that the BCE treatment exerted a significantly greater influence on the microbial community in B-contaminated, rendering it more comparable to that of the uncontaminated soil amended with either type of biochar.

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# Evaluation of nano-PbO and macro-PbO transformation in soil-plant system based synchrotron methods

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**ABSTRACT**

Nanotechnology is a rapidly evolving field in the 21st century. Nanomaterials, due to their ultra-small size, exhibit an extremely high surface area-to-volume ratio. These physical characteristics of nanomaterials contribute to their chemical and biological properties being significantly different from those of their macroscopic counterparts. The study employs advanced technological research methods lead oxide (PbO) nanoparticles based on synchrotron radiation (Kurchatov Synchrotron Radiation Source, Moscow). In a model experiment, the impact of macro- and nanoscale PbO particles on the processes of uptake and transformation in Haplic Chernozem soil, as well as on structural and functional alterations in the tissues and cells of spring barley (*Hordeum vulgare* L.) throughout its growth cycle, was investigated. The transformation and speciation of Pd were studied using a direct nondestructive physical method, including X-ray diffraction (XRD), X-ray absorption spectroscopy (XAS) and transmission electron microscopy (TEM). Newly formed crystalline mineral lead-containing compounds were identified in plant tissues: plumboferrite ($Pb_2(Fe_3^+, Mn_2^+, Mg)_{11}O_{19}$), litharge (PbO), galena (PbS), and pyromorphite ($Pb_5(PO_4)_3Cl$). The Pb content in plant samples was 25.4% for PbO-nano and 1.6% for PbO-macro. It was noted that in samples contaminated with PbO-nano, an incomplete phase transition from the tetragonal phase of PbO to the orthorhombic phase was observed. This supports the high transformation and penetration capacity of PbO nanoforms into barley plant tissues, followed by their accumulation and formation of new mineral phases. Molecular-structural data revealed a reduction in the coordination number to 2-3 atoms for the nearest atomic environment of Pb, a characteristic feature of soil and plant samples. High dispersion values of local interatomic distances in the nearest coordination spheres around the absorbing Pb atom were diagnosed, marked by short Pb—O distances close to 2.14 Å, typical of aqua complexes $Pb^{2+}(H_2O)n$. It was found that the toxicity of introduced PbO forms, especially nanoparticles, significantly affects the state of intracellular structures (mitochondria, plastids, and inclusions) involved in photosynthesis and energy metabolism, leading to destructive changes that reduce metabolic processes related to barley growth and development. The study demonstrates the potential of combining synchrotron methods and other instrumental techniques for characterizing and analyzing the behavior of nanoparticles in biological systems and organo-mineral polydisperse structures, such as soil.

**Acknowledgments**

The study was supported by the Ministry of Science and Higher Education using the equipment of the Center of Collective Use «Soil Bioengineering» (no. 075-15-2025-667)

**Keywords**

Lead, nanoparticles, contamination, forms of the compound, ultrastructure.

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# A Bacillus paramycoides strain and its application in wastewater treatment

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**ABSTRACT**

Chlortetracycline (CTC) is a major tetracycline antibiotic, which has been widely used in livestock and fish husbandry. The widespread presence of CTC in the environment poses a significant threat to both ecological environment and human health. Biodegradation is considered an effective method to reduce CTC in environments. In this study, the strain BCTC-2 was obtained from an activated sludge of a pharmaceutical plant, through enrichment, domestication, and isolation screening. BCTC-2 was identified as *Bacillus paramycoides* and possessing high CTC degradation capacity and good environmental adaptability. Meanwhile, we investigated the influence of different environmental conditions, such as incubation temperature, pH, external carbon source, initial CTC concentration, and inoculum amount for the activity of bacteria and CTC removal efficiency. Results indicated that the maximum removal efficiency of CTC could reach 84.15% under optimal conditions: initial concentration of 50 mg $L^{-1}$, sodium citrate as the external carbon source, 30°C, pH=7, and 5% inoculum. Additionally, BCTC-2 demonstrated effective degradation of CTC in actual wastewater containing antibiotics. Under conditions of 30°C and pH=7, strain BCTC-2 achieved a CTC degradation rate of 75.23%. This strain can be applied to the treatment of actual antibiotic-containing wastewater, reducing environmental pollution and health hazards caused by antibiotic residues. The present study confirmed the effectiveness and feasibility of using BCTC-2 for the biodegradation of CTC in wastewater, offering a promising strategy for mitigating CTC pollution in aquatic environments.

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# Phototransformation of New Organic Contaminants and Associated Biological Effects as Mediated by Smectite Clays

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## ABSTRACT

Smectite clays are ubiquitously present in soil with high abundances. They can retain and mediate the transformation of a variety of organic contaminants due to their large specific surface areas and high surface activities. Here, we examined the expression of tetracycline resistance gene *tet*(M) of a fluorescent *Escherichia coli* whole-cell bioreporter influenced by the phototransformation of tetracycline in the presence of smectite clays or humic substances. Despite the similar phototransformation ratios (80~90%) of the total loaded tetracycline after irradiation, the decrease ratios of cell fluorescence intensity were much higher with montmorillonite and hectorite (94% and 93%) than with Pahokee Peat humc acid and Pahokee Peat fulvic acid (44% and 69%) when compared to the respective dark controls. As illustrated by mass spectroscopic and chemical analyses, tetracycline was found to be transformed to amide (ineffective in inducing ARGs) with the presence of clays by reaction with self-photosensitized singlet oxygen ($^1O_2$), while the humic substances catalyzed the production of another two demethylated and/or deaminated compounds (still effective in inducing ARGs) in addition to the amide compound via reaction with triplet excited state dissolved organic matter ($^3$DOM*).

Additionally, we investigated photoaging processes of polystyrene and polyethylene microplastics deposited on surfaces of three representative Fe-bearing clay minerals (biotite, lizardite, and montmorillonite) under simulated sunlight and natural sunlight. We observed severe photoaging of the two microplastics catalyzed by Fe-bearing clay minerals at soil-air interfaces, manifested by intensifying morphological damage with increasing structural Fe content and 2 times more carbonyl groups than reported aqueous systems. These structural alterations, predominantly localized on microplastic surfaces, though accounting for merely 0.1% of total carbon, significantly enhanced their hydrophilicity and microbial affinity. This aggravation originated from boosted surface-bound hydroxyl radicals with prolonged half-life via light-driven Fenton-like reactions of Fe-bearing clay minerals. The direct light exposure of clay surfaces and interlayer confinement within nanosized clay interlayers facilitated *in-situ* oxidation of microplastics. Critically, photoaged microplastics possessed severe toxicity on luminescent bacteria, with maximum increase in acute toxicity units by 0.67. Enhanced microplastics photoaging and toxicity were also observed under natural sunlight within 7-day diurnal and wet-dry cycles, similar to the effects seen under 36-h continuous simulated sunlight.

The results clearly demonstrate that smectite clays can effectively mediate the phototransformation of tetracyclines and microplastics and in turn strongly affect their biologic effects.

**Acknowledgments**

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# Biochar downsizing: From bulk to nanoscale solution in soil remediation and contaminants immobilization

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**ABSTRACT**

The conversion of bulk biochar (b-BC) to nano-biochar (n-BC) via ball milling yields substantial physicochemical modifications, including enhanced specific surface area, increased pore volume, and shifts in elemental composition and surface functional chemistry, all of which depend on feedstock characteristics and pyrolysis conditions (Raczkiewicz et al., 2024a). Ball milling further reduces the concentrations and bioavailability of PAHs and heavy metals through mechanochemical degradation, defect generation, and improved adsorption efficiency (Raczkiewicz et al., 2024b).

However, nanoscale transformation is associated with elevated ecotoxicological risk; n-BC displays increased toxicity toward microbial communities, invertebrates, and plants relative to b-BC (Raczkiewicz et al., 2024c). Despite these hazards, n-BC demonstrates superior immobilization of potentially toxic elements (PTEs) and PAHs in contaminated soils, decreasing their bioavailability and plant uptake, including in lettuce (Raczkiewicz et al., 2025a). These effects arise from enhanced adsorption capacity and accelerated immobilization kinetics for metals such as Pb, Zn, and Cd (Raczkiewicz & Oleszczuk, 2025b). Optimization is achievable through targeted feedstock selection and pyrolysis under nitrogen. Overall, n-BC presents a duality of improved remediation performance and heightened ecotoxicological concern, underscoring the need for controlled production parameters to ensure environmentally responsible application.

**Acknowledgments**

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# Risk Ranking of Antimicrobial Resistance Across One Health Sectors: Leveraging Long-Read Sequencing and Methylation Analysis

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**ABSTRACT**

Antimicrobial resistance (AMR) represents a severe global health threat, undermining the effectiveness of treatments for infections and threatening human and animal health. Its rapid spread across humans, animals, and the environment complicates infection treatment and increases the risk of severe illness and death. The magnitude of AMR's impact demands a comprehensive, integrated approach commonly known as One Health, which recognizes the interconnected health of people, animals, and ecosystems. This framework calls for collaborative, multisectoral actions across human health, veterinary medicine, agriculture, and environmental management to address AMR sustainably and effectively.

The importance of risk ranking in AMR within a One Health framework lies in its ability to identify and prioritize the highest-risk antimicrobial resistance genes, pathogens, and transmission pathways across the human-animal-environment interface. AMR risk ranking provides a systematic approach to prioritizing antimicrobial resistance threats by integrating data on genetic context, mobility potential and host range of AMR genes. Risk ranking enables robust identification of high-risk resistance genes, pathogens, and exposure pathways for targeted surveillance and intervention strategies that are critical given the vast diversity of resistant agents and their complex transmission dynamics. By helping to assess where the greatest threats lie—whether in clinical settings, agriculture, or environmental reservoirs—risk ranking guides the implementation of policies such as antimicrobial stewardship, infection prevention and control, and environmental contamination reduction measures. These efforts are central to slowing the spread of resistance, preserving the effectiveness of antimicrobials, and ultimately protecting public health, animal welfare, and ecosystem resilience.

By using long-read metagenomics and methylation pattern analysis, we have developed a framework for predicting mobility and host range of AMR genes and determine their transmission routes across One Health sectors. Our results demonstrate the importance of non-clinical bacteria in acting as reservoirs and transmission vectors of AMR genes. The developed framework can be used to predict the latent AMR genes of greatest concern that could be the targets of future monitoring campaigns.

Recognizing AMR as a One Health threat and applying risk ranking approaches underpin the global fight against antimicrobial resistance by facilitating the design of focused, evidence-based, and sustainable interventions at local, national, and international levels.

# Global ecological and health risks of PFAS in surface soil

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFAS) are highly persistent and potentially toxic, making them a growing global concern. Yet, the large-scale ecological and human health risks of PFAS contamination in soils remain poorly understood. In this study, we synthesized about 2,000 PFAS concentration data points from surface soil samples reported in 106 peer-reviewed studies to evaluate global contamination patterns and associated risks. A probabilistic approach showed that long-chain legacy PFAS, particularly perfluorooctane sulfonic acid (PFOS), were the dominant contaminants in soil (median concentration 1.03 ng $g^{-1}$), with 30.32% of the grids exceeding safety threshold. We identified geographic hotspots that include Central Europe, the northeastern United States, and southeastern China. Notably, health risks linked to perfluorohexane sulfonic acid (PFHxS) are elevated in both Europe and the U.S (exceeded global median by a factor of 26.77). Moreover, short-chain PFAS exhibit higher mobility, suggesting a greater potential for groundwater leaching. These findings highlight the urgent need to establish global soil quality standards for PFAS and offer critical insights to guide public health policy and soil management strategies.

**Keywords:** PFAS; Surface soil; Ecological risk; Human health risk; Monte Carlo simulation.

**Acknowledgments**

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# Can Machine Learning Predict Plant Uptake of Per- and Polyfluoroalkyl Substances from Soils?

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**ABSTRACT**

Understanding plant uptake of per- and polyfluoroalkyl substances (PFAS) is crucial for assessing human exposure risks and ensuring food safety. Machine learning can be valuable in studying plant uptake of PFAS by recognizing hidden patterns in datasets and revealing new mechanistic insights. We trained four machine learning models, including eXtreme Gradient Boosting (XGBoost), Random Forest (RF), Multilayer Perceptron (MLP), and Support Vector Regression (SVR), to predict the bioconcentration factor (BCF) and concentrations (C) of 21 PFAS in plants using a newly compiled dataset composed of 11 crops, 11 plant tissues, as well as various soil properties and cultivation conditions. All models achieved satisfactory performance, and XGBoost achieved the best performance, with a coefficient of determination ($R^2$) of 0.951, mean absolute error (MAE) of 0.239, and root mean square error (RMSE) of 0.383 for Log BCF and $R^2$ of 0.943, MAE of 0.253, and RMSE of 0.386 for Log C, respectively. Soil pH and PFAS carbon chain length are identified as key predictors for Log BCF and soil PFAS concentration and growth-cycle duration for Log C. Root and leaf tissues are the primary compartments of PFAS accumulation within plants, exhibiting the highest BCF and concentration levels. Plant roots accumulate high levels of both long-chain and short-chain PFAS, whereas above-ground tissues (particularly leaves) favor the uptake and accumulation of short-chain PFAS. Notably, this chain-length selectivity was most pronounced at soil pH < 6, with BCF for long-chain PFAS in above-ground tissues dropping markedly. At soil pH > 6, the BCF range across all chain lengths narrowed among all tissues. We then retrained the XGBoost model with the 10 most influential predictor ($R^2$ > 0.95) to predict carrot root concentrations of 1051 PFAS in 11 soils. Carrot roots generally have greater Log C in alkaline soils (e.g., Alfisols) than in acidic soils (e.g., Mollisols). The number of fluorine atoms in PFAS negatively correlates with Log C, which is most pronounced in alkaline soils. These findings could help develop management and mitigation strategies to decrease PFAS accumulation in food crops and dietary exposure to humans.

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# Functional Resilience and Network Reorganization: How Plant-Associated Microbiome Maintain Ecosystem Services Under Antibiotic Pressure

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## ABSTRACT

Beyond compositional changes, antibiotics may disrupt microbial interaction networks and functional capabilities that underpin plant health and soil ecosystem services. Understanding functional responses to pharmaceutical stress is critical for assessing agricultural sustainability and food security risks. This study examined how antibiotic exposure affects bacterial co-occurrence networks, functional diversity, and predicted metabolic capabilities across the plant-soil continuum. Following lettuce cultivation in sulfamethoxazole (SMX) or trimethoprim (TMP) amended soil (3 mg $kg^{-1}$), we constructed co-occurrence networks using Spearman correlations ($|\rho| > 0.6$, $P < 0.05$) and predicted functional capabilities using FAPROTAX with custom mappings for antibiotic resistance, pathogen potential, and plant-beneficial functions. Effect sizes (Cohen's d) quantified biological significance beyond statistical differences, while functional diversity metrics assessed metabolic potential across compartments and treatments. Network analysis revealed that antibiotic pressure reduced bacterial connectivity and complexity, with control communities exhibiting ~50 nodes and ~160 edges compared to ~40 nodes and ~120 edges in SMX-treated soils. Despite structural simplification, positive co-occurrences dominated across all networks (~115 positive vs ~25 negative links), indicating maintained cooperative interactions. Functional diversity showed significant compartment effects (Shannon $P = 0.0017$; richness $P = 0.0039$; evenness $P = 0.016$), with endosphere communities exhibiting 25-30% lower functional diversity than bulk soil. Critically, antibiotic treatments selectively enriched xenobiotic degradation ($P = 0.042$) and secondary metabolism pathways, particularly in bulk soil, without systematically increasing pathogen-associated functions. Effect size analysis demonstrated that while antibiotic and organic compound degradation showed large biological effects (Cohen's $d \geq 0.8$), core plant-beneficial functions, including growth promotion, biocontrol, and nitrogen cycling, remained stable with negligible to small effect sizes. Risk assessment revealed that pathogen-related functional shifts, though statistically significant, represented minimal biological changes. Plant-associated bacterial communities demonstrate remarkable functional resilience through spatial organization, maintaining critical ecosystem services despite antibiotic-induced network disruption and compositional shifts. The selective enrichment of degradation pathways suggests microbiome-assisted mitigation potential for pharmaceutical residues. These findings support the development of compartment-targeted strategies to enhance agricultural sustainability under increasing pharmaceutical pressure.

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# Spatial Compartmentalization Overrides Antibiotic Effects in Shaping Plant-Associated Bacterial Communities: Insights from the Lettuce Microbiome

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**ABSTRACT**

Agricultural antibiotic contamination threatens crop productivity through disruption of beneficial plant-microbe associations. While antibiotic impacts on the soil microbiome are documented, the extent to which spatial compartmentalization across the plant-soil continuum buffers these effects remains poorly understood. This study investigated how bacterial community assembly patterns differ across bulk soil, rhizosphere, and endosphere compartments under environmentally relevant antibiotic exposure. Lettuce seeds were planted in soil amended with sulfamethoxazole (SMX) or trimethoprim (TMP) at 3 mg $kg^{-1}$, representing realistic agricultural concentrations. Full-length 16S rRNA gene sequencing (Oxford Nanopore Technologies) was performed on bacterial communities from bulk soil, rhizosphere, and endosphere compartments (n=45 samples across five treatments). Community structure was analyzed using alpha/beta diversity metrics, differential abundance analysis (ALDEx2, ANCOM-BC), and random forest machine learning classification. Result showed spatial compartmentalization emerging as the dominant driver of bacterial community structure, significantly exceeding antibiotic treatment effects (PERMANOVA: compartment $R^2 = 0.189$, $P = 0.001$; treatment $R^2 = 0.145$, $P = 0.139$). Endosphere communities exhibited substantially reduced alpha diversity compared to bulk soil and rhizosphere (Chao1 $P = 0.0001$), with distinct taxonomic signatures. Gammaproteobacteria dominated endosphere assemblages (up to 82.9% relative abundance in controls), while Alphaproteobacteria and Actinobacteria prevailed in soil compartments. Random forest classification achieved higher accuracy for distinguishing spatial compartments than antibiotic treatments, with *Methyloceanibacter superfactus* and Rhizobiaceae species serving as key discriminatory taxa. Core microbiome analysis revealed compartment-specific enrichment patterns: *Stenotrophomonas* (endosphere, ~0.9% abundance), *Microbacterium* (bulk soil), and *Herbaspirillum* (rhizosphere), with these patterns remaining stable across antibiotic treatments. Differential abundance analysis identified 68 ASVs significantly associated with compartment identity (FDR < 0.05), while treatment comparisons yielded minimal significant differences. Plant-mediated spatial filtering represents the primary mechanism structuring bacterial communities, effectively buffering core microbiome composition against pharmaceutical pressure. These findings suggest that compartment-specific microbiome management strategies may enhance agricultural resilience to emerging antibiotic contamination while maintaining beneficial plant-microbe associations critical for sustainable crop production.

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# Distribution and Fate of Per- and polyfluoroalkyl Substances in Sludge and Biosolids from Municipal Wastewater Treatment Plants across the United States

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## ABSTRACT

Biosolids generated from municipal wastewater treatment plants (WWTPs) are a major point source of per- and polyfluoroalkyl substances (PFAS) to the agricultural environments. PFAS compounds are considered the major class of contaminants of emerging concern; the occurrence and fate of PFAS in municipal wastewater treatment processes remain inadequately studied. In this study, we collected sludge and biosolids samples from twelve WWTPs across the United States and conducted target analysis for 43 PFAS chemicals using liquid chromatography coupled to tandem mass spectrometry using the modified EPA 1633 method. The sludge samples were separated into solid and liquid fraction and analyzed PFAS in each fraction. The highly hydrophilic PFAS such as short-chain PFAS were frequently detected in the liquid fraction while the more hydrophobic PFAS compounds were predominantly presented in the solid fractions. The total PFAS concentration ranged from 93 to 297 ng/g in the sludge samples and from 135 to 491 ng/g in the biosolids samples. PFAS distribution profiles in sludge/biosolids samples showed that the precursors including polyfluoroalkyl phosphate diesters (diPAP), perfluorooctane sulfonamidoacetic acids, and fluorotelomer carboxylic acids (FTCA) contributed approximately 90% of total PFAS, whereas legacy PFAS chemicals accounted for only a small fraction. Furthermore, our results demonstrated that the conventional sludge treatment processes such as anaerobic digestion followed by dewatering processes cannot remove PFAS effectively. In most WWTPs, elevated PFAS levels were observed in the biosolids samples which could be attributed to the reductions in biomass, biotransformation of precursor compounds and the changes in sorption capacity after the treatment processes. Significant variations in PFAS composition were found in sludge samples, but such variations were less pronounced for the PFAS in biosolids samples, which could be attributed to the similar treatment processes in WWTPs selected in this study.

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# Microbially Mediated Degradation Processes and Mechanisms of Flame Retardants in Soils

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**ABSTRACT**

Brominated flame retardants, represented by decabromodiphenyl ether (BDE-209), are widely accumulated in soils contaminated by electronic waste; however, the microbially driven transformation processes in soil environments remain poorly understood. Although previous studies have shown that some cultivable microorganisms are capable of debrominating BDE-209 and eventually utilizing it, integrated in situ multi-omics evidence linking contaminant removal with functional gene expression of uncultured soil microorganisms is still lacking. Here, soil microcosm incubation experiments were established using electronic waste–contaminated soils collected from Taizhou and Guiyu, amended with BDE-209, and monitored over a 90-day period for BDE-209 residues and bromide release, together with 16S rRNA gene amplicon sequencing, metagenomic, and metatranscriptomic analyses to characterize microbial responses. The results showed that BDE-209 was substantially degraded in both soils, with removal efficiencies of 77% and 74%, respectively, accompanied by continuous bromide release. Throughout the incubation, microbial community richness decreased significantly, and community composition exhibited pronounced stage-dependent successional patterns. In the later stages, lower-brominated polybrominated diphenyl ether congeners accumulated, resulting in increased overall toxicity potential and concurrent declines in microbial metabolic potential and transcriptional activity. Integrated multi-omics analyses indicated the involvement of debrominating microorganisms and their syntrophic partners, supporting a community level degradation mechanism whereby BDE-209 undergoes stepwise debromination by debrominators, followed by secondary transformation of lower brominated products by cooperative heterotrophic microorganisms. Overall, this study elucidates the microbially mediated degradation processes and mechanisms of BDE-209 in contaminated soils, offering mechanistic insight relevant to the management and remediation of brominated flame retardants at impacted sites.

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# Soil Biogeochemical Responses to Acid Mine Pollutants in Coal-Mined Inceptisols of Assam, India

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**ABSTRACT**

Open-cast coal mining generates substantial acid mine pollutants that disrupt soil biogeochemical functioning, particularly in the strongly acidic Inceptisols of Assam, India. Exposure of pyrite-bearing strata enhances Acid Mine Drainage (AMD), leading to mobilization of sulphates, sulphides, and trace metals that alter nutrient cycling, microbial processes, and soil structure. This study examined soil responses across four mining-related land-use stages namely CI (active mining), CII (5-year recovery), CIII (10-year recovery), and CIV (uncontaminated control) in paddy-growing landscapes affected by coal extraction. Soil acidity was most severe in CI, where surface soil pH averaged 3.79 and subsurface pH 3.72, gradually improving toward CIV (5.31 and 5.25, respectively). Organic carbon increased from 0.83% (CI) to 1.25% (CIV), accompanied by progressive increases in total and available Nitrogen, Phosphorus, and Potassium. Secondary nutrients also recovered, with Calcium rising from 2.20 to 4.49 mg/kg and Mg from 1.02 to 1.98 mg/kg.AMD signatures were evident in Sulphur fractions. Sulphate-S decreased from 7.13 mg/kg in CI to CIV with landscape redistribution, while sulphide-S declined sharply from 1.88 mg/kg (CI) to 0.20 mg/kg (CIV), reflecting oxidation of reduced sulphur minerals. Trace metals displayed clear pollutant gradients from CI to CIV, confirming strong metal mobilization under acidic conditions and gradual stabilization during recovery. Biological indicators revealed depressed activity near active mining areas. Soil microbial biomass carbon increased from 182.75 mg/kg (CI) to 237.50 mg/kg (CIV), with Urease and Phosphomonoesterase activities showing similar improvements. Bacterial and fungal populations recovered significantly across the sequence. Bulk density decreased from 1.66 to 1.25 g/cm³, reflecting structural regeneration and organic matter buildup. Overall, the study demonstrates that acid mine pollutants exert strong control over soil biogeochemical processes in coal-impacted Inceptisols. While natural recovery enhances chemical, biological, and physical properties, persistent acidity and metal loads remain critical constraints, highlighting the need for targeted soil remediation strategies.

**Keywords:** Acid mine drainage, Soil biogeochemistry, Trace metals, Inceptisols.

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# Bacterial Extracellular Vesicles as Vectors of Antimicrobial Resistance in Agricultural Soils

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**ABSTRACT**

Antimicrobial resistance (AMR) is a global health threat requiring a One Health approach across human, animal, and environmental sectors. Bacterial extracellular vesicles (BEVs) are membrane-bound particles secreted by bacteria that are capable of carrying genetic cargo. In previous research, we demonstrated the ubiquitous presence of BEVs in different environmental habitats, including dust, soil, and wastewater. Our results showed that BEVs serve as vectors for a large number of antibiotic resistance genes (ARGs), conferring resistance to diverse classes of antibiotics. In this study, we focus on agricultural soils as a direct One Health interface, investigating ARG profiles in BEVs from a long-term field experiment in which agricultural soils were managed using different fertilization regimes involving farmyard manure. Following the purification of the BEV fraction, we found the particle concentrations ranging from $1.45 \times 10^6$ to $2.23 \times 10^7$ particles/g soil. Metagenomic sequencing revealed that BEVs were predominantly released by the phyla *Pseudomonadota*, *Actinomycetota*, and *Bacteroidota*, which also represent the dominant phyla in the soils. Furthermore, these BEVs carried 12 types and 48 subtypes of ARGs, as well as mobile genetic elements and virulence factors, with profiles remaining consistent across soils treated with different fertilization regimes. These findings emphasize the importance of further investigating the role of BEVs in disseminating AMR in environmental microbiomes. Due to their ubiquitous presence and specific properties, BEVs may play a pivotal role in the dissemination of AMR across One Health sectors.

**Acknowledgments**

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# Biotransformation of tire-derived 6PPD and 6PPD-Q and metabolism alteration in rice plants under different exposure routes

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**ABSTRACT**

The tire-derived rubber antioxidant 6PPD is widely present in various environmental media, and the environmental toxicity of its oxidation product, 6PPD-Q, has attracted increasing attention. As one of the most extensively cultivated food crops, the uptake and biotransformation, of 6PPD/6PPD-Q, as well as their induced metabolism alteration in rice remains unclear. This study simulated two exposure pathways—root and foliar—along with two contaminants via hydroponic experiments to investigate the absorption, metabolism, and underlying mechanisms of 6PPD/6PPD-Q in rice. The results indicated that rice can take up 6PPD/6PPD-Q through both root and foliar pathways. After foliar uptake, reverse translocation occurred, leading to significant accumulation of 6PPD and 6PPD-Q in both roots and leaves. Under root exposure, the biotransformation of 6PPD and 6PPD-Q was dominated by quinone degradation, dealkylation, and hydroxylation, whereas foliar exposure resulted in a higher proportion of conjugated metabolites. Molecular docking further confirmed that 6PPD/6PPD-Q can stably bind to metabolic enzymes such as CYP450, UGT, GST, and CarE. Root exposure to 6PPD and 6PPD-Q significantly enhanced the activities of metabolic-related enzymes (CYP450, GST, UGT, CarE) in rice roots and up-regulated associated genes (CYP86A1, CYP72A17, GSTU6). Foliar exposure also activated defense mechanisms in rice. Untargeted metabolomics revealed that 6PPD and 6PPD-Q markedly perturbed amino acid metabolism, the TCA cycle, lipid metabolism, and nucleotide metabolism in rice. Specifically, energy supply and glutathione (GSH) synthesis were inhibited in roots, while membrane lipid and nucleic acid metabolism were impaired. In leaves, compensatory defense was achieved through enhanced TCA cycle activity, GSH synthesis, and unsaturated fatty acid production. Metabolic remodeling was more pronounced under root exposure compared to foliar exposure, and 6PPD-Q exhibited higher toxicity. This study systematically elucidates the uptake and metabolic patterns of 6PPD/6PPD-Q in rice under different exposure routes and highlights that foliar exposure represents a non-negligible risk pathway in agricultural scenarios.

**Acknowledgments**

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# Migration and Mitigation of Manure-borne Antibiotic Resistance Genes in Soil-vegetable Systems

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**ABSTRACT**

Antibiotic resistance genes (ARGs) have been recognized as emerging contaminants that can enter the human food chain via manure-amended agricultural soils. However, the migration of manure-derived ARGs in the soil–vegetable system and effective mitigation strategies remain unclear. Here, carrot and pakchoi were used as model vegetables to a) quantify human exposure to ARGs via vegetable consumption, and b) develop soil- and leaf-based interventions to control ARG dissemination.

High-throughput qPCR showed that manure application markedly promoted ARG enrichment in the carrot rhizosphere and tubers. ARG abundance, diversity and bioaccumulation factors were higher in leaves than in tuber tissues, and manure increased the bioaccumulation of multiple ARGs and mobile genetic elements (MGEs) in tubers. Carrots grown in manured soil could deliver up to ~$10^7$ ARG copies per person per day, while peeling carrots reduced ARG and MGE intake by up to 91% and 59%, respectively.

To mitigate antibiotic and ARG burdens in soil, a biochar-based biofilm (BB) carrying antibiotic-degrading bacteria was introduced into antibiotic-contaminated soils. BB accelerated sulfadiazine and trimethoprim dissipation and, after initial fluctuations, decreased the relative abundance and diversity of soil ARGs, particularly among antibiotic-degrading microorganisms, while limiting the introduction of exogenous ARGs and reducing pathogenic taxa.

To interrupt external ARG transfer routes, a magnetic biochar/quaternary phosphonium material (MBQ) was applied as a foliar spray on pakchoi. MBQ reshaped the phyllosphere community, inactivated antibiotic-resistant bacteria and reduced the abundance of high-risk human pathogens and ARGs on leaves; subsequent water washing further removed residual ARGs.

Overall, this work reveals the enrichment and transfer of manure-derived ARGs in the soil–vegetable continuum and proposes BB- and MBQ-based strategies that jointly target soil and phyllosphere pathways, providing technical support for controlling antibiotic resistance dissemination through vegetable production.

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# Photodegradation of clindamycin by biochar-derived dissolved organic matter is simultaneously regulated by ROS generation and binding effect

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## ABSTRACT

The combustion of biomass and fossil fuels releases vast amounts of carbon into the atmosphere, leading to global climate change. Up to 27% of these released carbon is retained as black carbon rather than emitted as greenhouse gasses. As an essential source of the natural dissolved organic matter (DOM), biochar-derived dissolved organic matter (BDOM) plays a vital role in the photodegradation of organics; however, there is rare information about the BDOM-induced photodegradation mechanism of clindamycin (CLM), one of the widely used antibiotics. CLM was shown to be degradable by a combination of zerovalent iron, $H_2O_2$ and ultrasonication, while the photodegradation mechanism of CLM by BDOM is still largely unknown.

Herein, we discovered BDOM-generated reactive oxygen species (ROS) stimulated CLM photodegradation. Hydroxy radical (•OH) could directly attack CLM by OH-addition reaction, the singlet oxygen ($^1O_2$) and superoxide ($O_2^{\bullet-}$) contributed to the CLM degradation by transforming to •OH. In addition, the binding between CLM and BDOMs inhibited the photodegradation of CLM by decreasing the concentration of freely dissolved CLM. Binding process inhibited CLM photodegradation by 0.25-1.98% at pH 7.0 and 6.1-41.77% at pH 8.5. These findings suggest that the photodegradation of CLM by BDOM is simultaneously regulated by the ROS production and binding effect between CLM and BDOM, benefiting the exact evaluation of the environmental impact of BDOMs.

**Acknowledgments**

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# Occurrence of pesticide residues under different land uses across Europe

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**ABSTRACT**

Pesticide residues in soils are an environmental concern that requires special attention due to their potential impacts on ecosystems and public health risk, especially in agricultural and urban areas. Different studies have been conducted to understand the occurrence and persistence of pesticide residues, primarily in similar land uses. Studies conducted under varying land-use and intensity conditions are scarce. In this context, this study aimed to assess the impact of land use on pesticide occurrence and to determine whether land use intensity influences pesticide occurrence. Soil samples were collected across five European biogeographical regions and countries: Alpine (Switzerland), Atlantic (NW Spain), Boreal (Latvia), Continental (West Germany), and Mediterranean (NE Spain). Five different land use types were selected in each biogeographical region: agricultural and seminatural (all regions), mining (4 regions), wetland, urban and forest (3 regions), and industrial uses (2 regions). Within each land use and region, three intensity levels were selected, ranging from the most degraded to the least degraded condition. Ten composite soil samples (each composed of five points) were collected from the 0-20 cm soil depth using the LUCAS methodology, resulting in a total of 770 soil samples for each combination of land use and intensity. Seventy-two pesticide residues were analyzed using the QuEChERS method for the determination of pesticide residues in foods of plant origin and adapted to measure pesticide residues in soil samples. The determination of multi-pesticides residues was carried out by UPLC-MS/MS and GC-MS/MS. At least one pesticide residue was detected in 318 samples (41% of the analyzed samples), with pesticide amounts ranging from 1 to 6633.8 ng/g. By land use, pesticide residues have not been detected in industrials land uses, whereas they are frequently found in urban and agricultural uses (except in the Boreal region). At least 25 pesticide residues or their metabolites were detected, with the most common residue (>5% occurrence) being Hexachlorobenzene (19%), p,p`-DDE (11.8%), Methyl parathion (11.3%), Tebuconazole (6.62%), Boscalid (6.5%) and o,p-DDT+p,p`-TDE (DDD) (5.8%). Although DDT-related pesticides were banned several decades ago in Europe, they appear in different study areas and land uses, highlighting their persistence over time. Further assays will focus on the analysis of glyphosate-related compounds and the risk assessment analysis of the studied samples, as well as the potential risk to inhabitants.

**Acknowledgments**

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# Sulfamethoxazole Transformation by Heat-Activated Persulfate: Linking Transformation Products Patterns with Compound-Specific Isotope Analysis

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**ABSTRACT**

Sulfamethoxazole (SMX) is a frequently detected sulfonamide antibiotic in surface and groundwater, raising environmental concerns about its fate. Oxidative treatments, such as persulfate application, are commonly used for micropollutant removal. To investigate and differentiate SMX transformation by various radicals from other SMX dissipation processes using multi-element compound specific isotope and transformation products (TP) analysis, SMX transformation experiments were conducted using heat-activated persulfate at pH 3, 7, and 10. SMX hydroxylamine (TP269a) and TP178 were identified as the dominant transformation products across all pH levels. The exclusive formation of 4-nitroso-SMX, 4-nitro-SMX, and TP518 at pH 3 highlighted the role of $SO_4^{\bullet-}$ in attacking the amino group. At pH 7 and pH 10, 3A5MI emerged as the dominant TP. Normal carbon isotope fractionation ($\Delta\delta^{13}C$ from 1.9‰ to 2.3‰), with consistent isotopic values across pH levels, was attributed to the formation of TP178, which involves C-S bond cleavage. An inverse nitrogen isotope fractionation at pH 3 ($\varepsilon_N = +0.68 \pm 0.11$‰) was linked to $SO_4^{\bullet-}$-induced single-electron transfer, leading to the formation of N-centered SMX radicals. Conversely, normal nitrogen isotope fractionation at pH 10 ($\varepsilon_N = -0.27 \pm 0.04$‰), was associated with multiple bond cleavages, including N-H bond cleavage initiated by H ABSTRACTion through HO• and N-S bond cleavage leading to the formation of 3A5MI. The inverse nitrogen isotope fractionation observed at pH 7 indicated that the dominant pathway involved $SO_4^{\bullet-}$ reactions, accounting for 76% of the overall transformation. Overall, the results highlight the potential of CSIA to elucidate SMX persulfate oxidation pathways and evaluating the natural attenuation of SMX through radical reactions in aquatic systems.

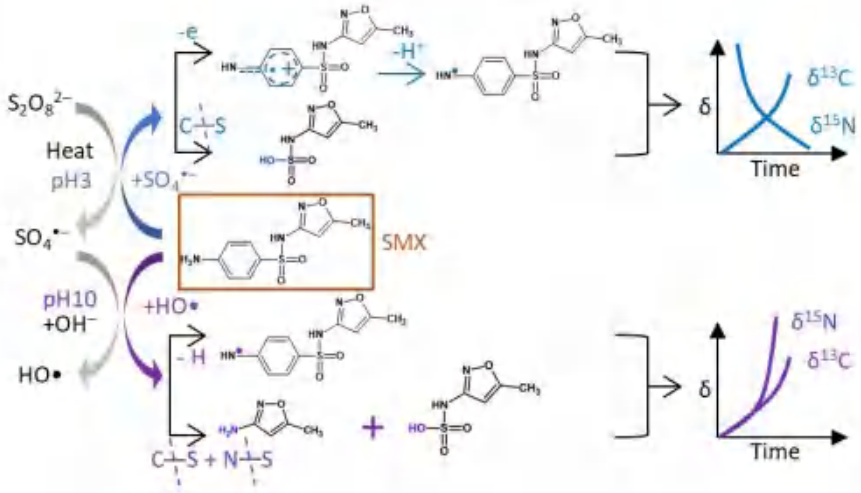



Figure 1. Overview of SMX persulfate oxidation with main pathways and related isotope fractionation

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# Fluorinated Pesticides Pose Emerging Global Environmental Risks

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## ABSTRACT

Ensuring food security remains one of the major global challenges. To sustain crop productivity, pesticides have become widely adopted in modern agriculture as highly effective chemical tools. Among them, fluorinated pesticides now account for more than half of newly registered pesticides worldwide, owing to the incorporation of fluorinated functional groups that enhance biological efficacy and chemical stability. However, the increasing reliance on these compounds occurs against a broader backdrop of rising chemical pollution, which has been linked to the transgression of Earth's planetary boundary associated with novel entities. Despite their extensive use, understanding of the environmental fate, transformation processes, and long-term ecological consequences of fluorinated pesticides remains limited.

Here, we synthesize current knowledge on fluorinated pesticides from a life-cycle perspective, encompassing their historical development, mechanisms of action, environmental fate, degradation pathways, and toxicological effects. Available evidence indicates that fluorinated pesticides exhibit substantial mobility across environmental compartments, including soil, freshwater, atmosphere, and biota, allowing transport beyond treated agricultural areas at regional to global scales. Environmental transformation through hydrolysis, photolysis, and biodegradation leads to the formation of diverse degradation products, some of which persist in the environment and exhibit toxicities comparable to or greater than those of the parent compounds. Toxicological studies demonstrate that fluorinated pesticides pose disproportionate risks to non-target organisms, particularly insects and aquatic species. Reported adverse effects include neurotoxicity, endocrine disruption, reproductive impairment, and immunotoxicity, indicating a potential for ecosystem-level impacts.

Special attention is highlighted to the debated formation of trifluoroacetic acid (TFA), an ultra-short-chain per- and polyfluoroalkyl substance increasingly detected in global water resources. Experimental evidence suggests that TFA formation from fluorinated pesticides is highly compound-specific and dependent on degradation pathways, indicating that current global mass-balance estimates may overestimate their contribution to environmental TFA burdens. This uncertainty highlights the need for improved mechanistic understanding and internationally harmonized monitoring strategies.

Overall, the frequent occurrence of trifluoromethyl-containing structures among highly toxic pesticides underscores a fundamental trade-off between chemical design for agricultural efficacy and long-term ecological safety. By integrating fragmented evidence into a unified global framework, this work identifies key knowledge gaps related to metabolite toxicity, chronic low-dose exposure, and cumulative multi-stressor effects across ecosystems. These findings emphasize the importance of evaluating fluorinated pesticides not only as local agricultural inputs, but also as globally relevant stressors within coupled food, environment, and health systems, thereby informing sustainable pesticide development and international risk governance.

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# Screening Non-Antibiotic Antimicrobial Agents in Environmental Matrices Using Interpretable Machine Learning and High-Resolution Mass Spectrometry

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**ABSTRACT**

Antimicrobial resistance is recognized as a major global public health challenge. In addition to antibiotics, non-antibiotic antimicrobial agents that are ubiquitous in the environment may also exert selective pressure on microbial communities; however, their environmental occurrence and resistance risks have long been underestimated. In this study, we integrated high-resolution mass spectrometry with machine learning to develop an intelligent screening framework for antimicrobial chemicals in soil matrices. An interpretable graph neural network was constructed to predict the antimicrobial activity of industrial chemicals, outperforming conventional models across multiple evaluation metrics and enabling efficient identification of potential non-antibiotic antimicrobial agents from large chemical inventories. Guided by model predictions, suspect and nontarget mass spectrometric analyses were subsequently applied, allowing high-throughput identification of diverse antimicrobial compounds in environmental samples, including antibiotics, disinfectants, and their transformation products. Overall, this data-driven approach substantially enhances the discovery efficiency of antimicrobial contaminants and provides a novel tool for systematically assessing the potential contribution of non-antibiotic antimicrobials to environmental antimicrobial resistance, thereby supporting the prioritization and risk assessment of emerging contaminants.

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# Antibiotic Residues, Microbial Ecology, and Greenhouse Gas Production in Manure: An Integrated One Health Perspective

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**ABSTRACT**

The widespread use of antibiotics in livestock poses environmental and public health risks due to their persistence in manure. This study examined the fate of Tylosin (100, 700 mg $kg^{-1}$), Enrofloxacin (29, 200 mg $kg^{-1}$), and Oxytetracycline (229, 1600 mg $kg^{-1}$) in cattle manure under aerobic incubation for 110 days, and their impacts on microbial communities and associated $CH_4$ and $N_2O$ emissions. Antibiotics were quantified by LC-MS/MS, and microbial DNA analyzed via shotgun metagenomics. All antibiotics showed biphasic degradation, with rapid loss in the first 21 days: Tylosin degraded most (99.0%), followed by Enrofloxacin (83.4%) and Oxytetracycline (73.3%). Microbial community alpha diversity was stable, but shifts were separated primarily by antibiotic class. Treatment explained ~21% of between-sample variation ($p = 0.001$). Concentration explains an additional ~3%. False Discovery Rate-corrected correlations linked functional groups to greenhouse gas fluxes: *Pseudomonadota* and *Bacteroidota* were positively associated with both gases, $CH_4$ ($\rho$=0.51) $N_2O$ ($\rho$=0.47). *Ignavibacteriota* showed the strongest positive associations, $CH_4$ ($\rho = 0.62$), $N_2O$ ($\rho = 0.61$), whereas *Planctomycetota* were negatively associated ($\rho = –0.85$), and *Verrucomicrobiota* $\rho$=-0.31. There was a temporal recomposition from *Proteobacteria* to *Bacteroidota* modulated by the treatments. Methanogens were more evident at later storage of manure. Antibiotic residues alter microbial dynamics and functional groups linked to greenhouse gas emissions, emphasizing the need for improved manure management, including longer composting, to mitigate ecological risks.

**Keywords:** antibiotics elimination, nitrogen functional genes, microbial communities' abundance, biogeochemical cycling, environmental risk

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# Adsorption of antibiotics by natural clay minerals

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**ABSTRACT**

Complex interactions between antibiotics of the tetracycline (oxytetracycline), aminoglycoside (gentamicin), amphenicol (chloramphenicol), and sulfonamide (streptocide) groups and natural bilayer (kaolinite) and trilayer (bentonite, expanded (heat-treated) vermiculite) clay minerals were studied. It was shown that clay minerals of various structures and of all groups can be effective sorbents of hydrophilic antibiotics (oxytetracycline and gentamicin).

The obtained experimental data were approximated by the Langmuir, Freundlich, and Dubinin-Radushkevich adsorption models. According to the Langmuir model, the maximum adsorption of oxytetracycline increased in the order: kaolinite < bentonite < vermiculite. The maximum Langmuir constant was characteristic of bentonite, while the minimum was for vermiculite. The maximum adsorption of gentamicin by minerals was somewhat lower in comparison with oxytetracycline, with bentonite also exhibiting the maximum binding strength. According to the Freundlich equation, the 1/n values are in the range of 0.6-0.9. The adsorption energies of antibiotics calculated using the Dubinin-Radushkevich model are less than 8 kJ/mol, suggesting that physical adsorption is predominant.

The influence of sorption solution properties: pH, ionic strength, and temperature on the adsorption of antibiotics on bentonite and kaolinite was studied. The acidity of the sorption solution is key for the adsorption of hydrophilic antibiotics, as most of their molecules have more than one ionic state, and protonation of the edge functional groups of the minerals themselves is also possible under the influence of pH. Ionic strength influences the adsorption of antibiotics on natural clay minerals at relatively high ionic strengths in solution. Competitive adsorption was more pronounced for kaolinite, which has a lower adsorption capacity. Increasing temperature from 283 to 303 K leads to a steady decrease in the maximum adsorption (Langmuir equation), indicating the exothermic nature of the sorption.

The structural changes of clay minerals under the influence of antibiotics were studied using FTIR spectroscopy and X-ray diffraction. The IR spectra of the reaction products show bands with high extinction coefficients and the highest number of identical groups in the molecule ($-CH_2-$ groups in the alkyl components of antibiotic molecules). X-ray diffraction showed that oxytetracycline at a concentration of 15 mmol/L alters the structure of kaolinite (a new peak appears). Exposure of bentonite to oxytetracycline at concentrations of 0.3-15 mmol significantly increases the basal reflex $d_{001}$.

Based on these results, practical recommendations are proposed for the use of natural clay minerals to remove hydrophilic antibiotics from contaminated water and soil solutions.

**Acknowledgments**

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# Exposure to cypermethrin pesticide disturbs the microbiome and disseminates antibiotic resistance genes in soil and the gut of Enchytraeus crypticus

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**ABSTRACT**

Worldwide, pyrethroids, such as cypermethrin, are the second most applied group of insecticides, however, their effects on the soil microbiome and non-target soil fauna remain largely unknown. Herein, we assessed the change of bacterial communities and antibiotic resistance genes (ARGs) of soil and in the gut of the model soil species *Enchytraeus crypticus* using a combination of 16S rRNA gene amplicon sequencing, and high-throughput qPCR of ARGs. Results indicate that cypermethrin exposure enriches potential pathogens (e.g. *Bacillus anthracis*) in the soil and gut microbiome of *E. crypticus*, heavily disrupting the latter's microbiome structure, and even disrupts activities of the *E. crypticus* immune system. The co-occurrence of potential pathogens (e.g. *Acinetobacter baumannii*), ARGs, and mobile genetic elements (MGEs) revealed the increased risk of pathogenicity as well as antibiotic resistance in potential pathogens. Moreover, structural equation modeling demonstrated that the dissemination of ARGs was not only promoted by MGEs, but also by the ratio of the core to non-core bacterial abundance. Collectively, these results provide an in-depth view of the previously unappreciated environmental risk of cypermethrin on the dissemination of ARGs in the soil and non-target soil fauna.

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# Nationwide Screening and Priority Ranking of Plastic Additives in Agricultural Soils of China

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**ABSTRACT**

Agricultural soils act as an important sink for plastic additives released from agricultural plastics and other anthropogenic sources; however, their chemical diversity, environmental behavior, and ecological risks remain poorly characterized at large spatial scales. In this study, a nationwide survey of agricultural soils across China was conducted to systematically identify plastic additives, characterize their environmental occurrence, investigate the drivers of their spatial distribution, assess ecological risks, and establish management priorities. An integrated "all-in-one" analytical strategy combining target, suspect, and non-target screening based on high-resolution mass spectrometry (HRMS) was employed to comprehensively capture both known and previously overlooked plastic additives in agricultural soils.

In total, 196 plastic additives belonging to 14 chemical classes were identified, including 109 confidence level 1 (CL1), 29 CL2, and 56 CL3 compounds. Among these, 86 compounds were reported for the first time in agricultural soils. Organophosphate (OPs), phenols (PHs), and phthalate esters (PAEs) dominated in both detection frequency and concentration levels. The concentrations of OPs, PHs, and PAEs ranged from 316.29–5828.54 ng/g, 83.84–14904.73 ng/g, and 15.69–14544.23 ng/g, respectively, with median values of 1000.85, 681.19, and 484.78 ng/g. Tri-OPEs and di-OPEs were the predominant OP subclasses, while hindered phenolic antioxidants occurred at substantially higher concentrations than bisphenols, indicating their strong sorption affinity and accumulation potential in soils.

At the national scale, total concentrations of plastic additives exhibited a pronounced west–east gradient, with higher levels observed in western and southwestern regions compared to eastern China. Mulched farmlands showed significantly higher additive concentrations than non-mulched soils, highlighting agricultural plastic films as a major direct source of plastic additives. Correlation analysis and Mantel tests further demonstrated that, in addition to plastic film usage and socioeconomic factors, climatic variables played a key role in controlling the spatial distribution of OPs. Solar radiation, total irradiance, sunshine duration, and relative humidity were strongly associated with OP distributions, particularly for novel organophosphate esters (NOPEs). This pattern suggests that environmental transformation processes, rather than direct emissions alone, largely govern their environmental occurrence. These results support the hypothesis that phosphite antioxidants can serve as important precursors of more stable phosphate esters through oxidative transformation in soils.

Ecological risk assessment based on mixture risk quotients indicated that plastic additives in agricultural soils pose overall medium-to-high ecological risks, with higher risk levels observed in mulched farmlands in western China. Tri-OPEs and di-PAEs were the primary contributors to mixture risks, whereas bisphenols and phenolic antioxidants generally contributed less at the national scale. Notably, novel and traditional additives exhibited comparable cumulative risk levels. A ToxPi-based prioritization approach integrating persistence, bioaccumulation, mobility, toxicity, environmental concentrations, and detection frequency identified BDtBPP, AO245, AO1076, AO1024, AO4426, AO168=O, DCHP, and DDP as high-priority substances for management. Several of these compounds—particularly novel OPEs, hindered phenolic antioxidants, and their oxidation products—are currently underrepresented in existing regulatory frameworks.

Overall, this study provides the first nationwide and systematic assessment of plastic additives in agricultural soils in China, highlights the critical role of environmental transformation processes in shaping additive profiles, and underscores the need to expand regulatory attention beyond traditional plastic additives to include emerging and transformed compounds in agricultural ecosystems.

**Keywords:**
Agricultural soils; Plastic additives; Pollution characteristics; Risk-based prioritization; Environmental processes

# Effects of predator-prey interactions on driving the evolution of bacterial antibiotic resistance

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**ABSTRACT**

Biological factors, especially predator-prey interactions, are crucial drivers of ecological processes. However, their roles in driving the evolution of antibiotic resistance, a global health concern, remain poorly understood in complex natural soil ecosystems. Predatory protists and predatory bacteria are primary bacterial predators, however, mechanisms underlying the influence of their predation on the richness and abundance of bacterial antibiotic resistance within a multitrophic soil ecosystem are still poorly known. Here, we assessed effects of soil predatory protists on predatory bacteria and antibiotic resistance genes (ARGs) across a gradient of protist concentrations under the control of bacteria's competitors – fungi. Our findings reveal that high-protist predation pressure significantly amplified the relative abundance of predatory bacteria *Streptomycetales* and *Myxococcales* between days 15 and 45 of the microcosm incubation. Aligning with a rising abundance of predatory bacteria and antibiotic-producing bacteria, the relative abundance and diversity of soil ARGs significantly increased under high protist concentrations, regardless of fungal effects. Many ARGs encoding key resistance mechanisms (antibiotic deactivation and efflux pumps) were enriched in response to predatory protists within complex inter-group interactions. Moreover, these enriched ARGs were strongly associated with both predatory bacteria and predatory protists. More profound effects of predatory protists on the predatory bacteria and soil ARGs were identified in the presence of fungi. Our study provides novel evidence about crucial effects of predatory protists on shaping the predatory bacterial community and driving bacterial antibiotic resistance under complex multitrophic interactions in a natural soil. These findings pave the way for future research aimed at mitigating this global health issue and uncovering other ecological processes.

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# Mitigation of antibiotic resistance genes in agricultural soil by Fe/Mn oxides functionalized biochars via suppressing horizontal gene transfer

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**ABSTRACT**

The rapid spread of antibiotic resistance genes (ARGs) in agricultural soils poses a threat to global ecological security and public health under the One Health framework. The application of biochar-based functional materials is a promising strategy for controlling biological pollutants in soils. However, the impacts of Fe/Mn oxides functionalized biochars (Fe/Mn-MBCs) for controlling ARGs in agricultural soils is still unknown. Therefore, the effects and mechanisms of Fe/Mn-MBCs on the abundance of ARGs and mobile genetic elements (MGEs) in agricultural soils were investigated via a 60-day microcosm experiment, combined with plasmids-mediated conjugation and natural transformation models. The results showed that Fe/Mn-MBCs significantly reduced total ARGs abundance by 20.95–42.94%, following the order MnBC > FMBC > FeBC. MGEs abundance decreased by 10.60–40.80% and showed positive correlations with ARGs, indicating that the reduced ARG pollution was achieved by Fe/Mn-MBCs weakening MGE-mediated horizontal gene transfer (HGT). Specifically, Fe/Mn-MBCs effectively inhibited bacterial conjugation (53.26%–66.11%) by decreasing cell membrane permeability, disrupting energy metabolism, and suppressed transformation (39.08%–76.06%) by adsorbing extracellular ARGs (eARGs) to reduce bioavailability, primarily due to the presence of oxygen-containing functional groups and Fe/Mn oxides ($Fe_3O_4$, $Mn_3O_4$, $MnO_2$) on biochar surfaces. Moreover, Fe/Mn-MBCs enhanced microbial diversity and niche filtering, consequently inhibiting ARG-hosting bacteria by 23.80–50.80%. Structural equation model analysis demonstrated that MGE-mediated HGT was the primary driving factor in the mitigation of soil ARG pollution by Fe/Mn-MBCs. These results demonstrate that Fe/Mn-MBCs effectively mitigate soil ARGs by inhibiting HGT, offering insights for the practical application and rational design of functionalized biochars as an in-situ remediation strategy against soil ARG pollution.

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# Plastic and Non-Plastic Microfibre Biodegradation in Soil: Monitoring the Impact

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**ABSTRACT**

Microfibre pollution is of growing global concern [1]. One of the main ways microfibres are released into the environment is from textile laundering via waste-water treatment plants (WWTP) into rivers and waterways [2]. However, microfibres are also introduced to terrestrial environments as in these WWTP, microfibres also make their way into sewage sludge, which is then applied to agricultural land as fertiliser [3]. Therefore, further work is needed into the impact of microfibres in soil environments.

In addition, microfibres are often categorised as part of the microplastic problem, however, studies have shown that cotton microfibres are the most prevalent in the environment [4]. These non-plastic microfibres often have chemical dyes and finishes applied during manufacturing so pose a potential risk to soil environments [5]. Despite this, existing research is more focussed on plastic microfibres resulting in a gap in research into impact of non-plastic microfibres such as cotton and wool.

This project aims to investigate the impact that decomposition of plastic and non-plastic microfibres, dyed and undyed, have on soil environments. A textile biodegradation experiment has been set up comparing dyed and undyed cotton and wool (examples of non-plastic textile microfibres) alongside virgin polyester, recycled polyester from polyethylene terephthalate (PET) bottles and recycled polyester from sea waste (examples of plastic textile microfibres). These textile samples (5 x 5 cm squares) and soil samples are being monitored over 18 months using Pyrolysis-GC-MS and LC-MS to trace chemical changes over time, as well as monitoring impacts to soil properties and soil function. Here we present preliminary data, focussing on the changes to textile and soil properties after 6 months.

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# Ecological Risks of Antibiotic Residues and Bioremediation in Agricultural Soils

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**ABSTRACT**

After nearly a decade of investigation into antibiotics in the agricultural soils of the North China Plain, tetracyclines (TCs) and quinolones were identified as the dominant antibiotics, exhibiting the highest detection frequency and concentrations, which ranged from 1.62 to 4238 μg·kg$^{-1}$. Notably, the concentrations of tetracycline metabolites (MTCs, particularly the 4-epimers of TCs) in soil were nearly equivalent to those of the parent compounds. Long-term manure application was found to contribute to the accumulation of TCs in soil, with higher antibiotic levels observed in greenhouse soils compared to open-field soils. Elevated antibiotic concentrations in soil tended to reduce microbial diversity and alter the structure and composition of soil microbial communities. An antibiotic resistome emerged in soils where antibiotic residues exceeded 300 μg·kg$^{-1}$. Based on a weighted comprehensive pollution index and risk quotient assessment, high ecological risk was identified in 9 out of 32 soil samples, while the remaining 23 samples posed a medium ecological risk. Laboratory-controlled experiments demonstrated that TCs and their 4-epimers (MTCs) are interconvertible in soil. Given their significant conversion potential to TCs, slow degradation rates, and potential impacts on soil microbes and antibiotic resistance genes (ARGs), the environmental risk posed by TC 4-epimers cannot be overlooked. Two ecologically distinct earthworm species—the epigeic *Eisenia fetida* and the endogeic *Metaphire guillelmi*—significantly accelerated the degradation of both TCs and MTCs in soil. *Eisenia fetida* notably promoted the proliferation of the degradation gene *tetX*, whereas *Metaphire guillelmi* enhanced interspecific relationships among soil microorganisms. In general, earthworm amendment improved the bioaccessibility of TCs and stimulated indigenous microbial activity, thereby facilitating TC degradation. Furthermore, earthworm addition reduced interspecific bacterial interactions and the relative abundance of mobile genetic elements (MGEs), which contributed to limiting the dissemination of ARGs. Additionally, earthworm application substantially mitigated the accumulation and transmission risk of antibiotics and ARGs from soil to lettuce. Collectively, these findings enrich the existing database, provide a scientific References for controlling antibiotic contamination in agricultural soils, and offer a cost-effective bioremediation strategy to address antibiotic and ARG pollution, thereby helping to ensure vegetable safety and human health.

# Adsorption Study of Sulfamethoxazole and Ciprofloxacin on Soil and Biochar Composite

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## ABSTRACT

Pharmaceutical pollution has always been a grave concern in global hydro-geosphere regions especially in emerging economies like India, China, Brazil, and Russia where there is a mismatch between the application and development of pharmaceuticals coupled with their effective removal strategies using advanced technologies.[1] Sulfamethoxazole (SMX), a sulfonamide antibiotic and ciprofloxacin (CIX), a fluoroquinolone group antibiotic have been recognized to exert negative effects on soil and water due to its mobility and widespread usages globally but particularly in India.[2] This current study investigated the removal of SMX and CIX with biochar (pine needle derived) material (0.05g, 0.125 g and 0.25 g) mixed with 5g soil. The Brunauer-Emmett-Teller (BET) method and surface morphological analysis, using a field emission scanning electron microscope (FE-SEM), revealed a porous biochar surface whereas energy-dispersive X-ray spectroscopy (EDS) analysis showed the co-existence of different minerals (i.e. Ca, S, K, Fe and Si) indicating the suitability of biochar materials as antibiotic sequestration agents from the soil solution. Changes in peaks were observed after SMX and CIX adsorption through Fourier transform infrared (FT-IR) and Raman spectroscopic measurements suggesting the involvement of chemisorptions for the removal mechanism. Batch sorption studies were performed to optimize experimental parameters for maximum removal of SMX and CIX. The shaking time was about 24 hrs with the equilibrium attained at 600 min. The samples were taken at time intervals of 0, 30, 60, 120, 240, 360, 480, 600 and 1440 minutes. Maximum removal (>65%) of SMX and CIX was observed for pine needle biochar and soil mixture at 50 µg $L^{-1}$ initial concentration of antibiotics, 25±2°C temperature, and 600 min contact time. Among the different adsorbent dosages, 0.25g for biochar was selected as an optimum dosage (maximum adsorption capacity ≈ 188 µg $g^{-1}$). The Langmuir isotherm ($R^2$>0.97) and pseudo-second order kinetic model ($R^2$>0.92) supported the data of SMX and CIX adsorption onto biochar. The adsorption with adsorbent concentration of 0.05g and 0.125g were <40% of maximum adsorption capacity. The SMX and CIX removal can be facilitated through different mechanisms like charge/ion-dipole interaction, pore-filling, Vander Waals interaction, electrostatic interaction and pi-pi interactions.

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# Climate-Driven Soil Processes Controlling the Fate of Sulfamethoxazole and Environmental Antimicrobial Resistance in Tropical Agro-Riverine Systems of Vietnam

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## ABSTRACT

Antimicrobial resistance (AMR) has emerged as one of the most pressing global public health and environmental challenges, particularly in low- and middle-income countries where antibiotic use in human medicine and livestock production is intensive and poorly regulated. A substantial proportion of administered antimicrobials is excreted unchanged or as active metabolites and subsequently released into soils and aquatic environments through manure application, wastewater discharge, and irrigation practices. Once introduced into the environment, antibiotics may persist, undergo transformation, or be remobilized, while simultaneously exerting selective pressure on microbial communities that promotes the emergence and dissemination of antibiotic-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs). These processes are especially dynamic in tropical agroecosystems, where high temperatures, strong seasonal rainfall, and fluctuating soil moisture strongly influence soil biogeochemical processes.

Vietnam represents a regional hotspot for environmental AMR due to high antibiotic consumption, dense human and animal populations, and limited wastewater treatment infrastructure. In peri-urban areas of Hanoi, agricultural production systems are closely connected to polluted rivers receiving untreated domestic, hospital, and livestock effluents. Thanh Tri district, located along major river systems, was selected as a pilot site to assess both the prevalence of environmental AMR and the underlying environmental behavior of antibiotics. Household surveys indicated that approximately 38% of households had used antibiotics for human treatment and 44% for animal production, suggesting continuous and diffuse antibiotic inputs into surrounding soils and water bodies.

To characterize environmental reservoirs of AMR, a total of 180 samples from household and geographic environments (including soil, sediment, groundwater, wastewater, and river water) were collected and analyzed for indicator bacteria listed under the Global Antimicrobial Resistance and Use Surveillance System (GLASS). Escherichia coli, Salmonella spp., and Staphylococcus aureus were detected at prevalences of 33.3% (95% CI: 23.9–44.1), 15.6% (95% CI: 9.1–25.0), and 12.2% (95% CI: 6.6–21.2), respectively. Molecular analysis revealed widespread resistance determinants, with sulfonamide resistance genes (sul1–sul3) present in approximately 14.52% of isolates. Resistance genes associated with aminoglycosides (20.13%), beta-lactams (16.17%), tetracyclines (13.2%), chloramphenicols (12.28%), and colistin (0.99%) were also detected. Antibiotic-resistant E. coli was the most prevalent, followed by Salmonella spp. and S. aureus, highlighting the role of river-connected agricultural landscapes as environmental reservoirs of AMR with potential implications for human and animal health.

To mechanistically link antibiotic residues with environmental AMR, a lysimeter-based field experiment was conducted to investigate the fate of sulfamethoxazole (SMX), a widely used sulfonamide antibiotic frequently detected in Vietnamese environments. The experiment was carried out using a tropical soil and lettuce (Lactuca sativa) as a representative leafy vegetable. SMX concentrations were monitored in soil and plant tissues over a 56-day cultivation period, while air temperature, relative humidity, and rainfall were continuously recorded.

SMX exhibited a pronounced biphasic dissipation pattern in soil. During the initial phase (0–7 days), more than 95% of extractable SMX was lost, with estimated half-lives of approximately 1.3–1.5 days. This rapid decline is attributed to strong sorption to soil constituents, rapid microbial or abiotic transformation, and redistribution from the readily extractable pool. In the intermediate phase, non-monotonic behavior was observed, with temporary rebounds in SMX concentrations following rainfall and periods of high humidity. These fluctuations indicate climate-driven desorption and remobilization processes that can temporarily increase SMX bioavailability. During the late phase, SMX concentrations declined again, reaching less than 1–2% of the initial input by the end of the experiment.

Compound-specific stable carbon isotope analysis (CSIA, $\delta^{13}C$) was applied to distinguish microbial transformation from physical redistribution processes. Trace levels of SMX were detected in lettuce roots and edible tissues throughout the cultivation period. Although concentrations in plants were low, $\delta^{13}C$ signatures confirmed soil to water transfer of SMX or its transformation products, highlighting a potential pathway for chronic low-level human exposure. Isotopic fractionation observed in soil samples further indicated ongoing microbial transformation and partial incorporation of SMX-derived carbon into soil organic matter.

By integrating environmental surveillance of ARB and ARGs with field-scale investigations of antibiotic fate, this study demonstrates that tropical soil–water–crop systems function as dynamic interfaces linking antibiotic inputs, climate-driven soil processes, and environmental AMR. Climatic variability modulates antibiotic persistence and remobilization, thereby influencing selective pressure on environmental microbial communities. These findings underscore the importance of coupling antibiotic fate studies with resistance monitoring within a One Health framework to improve risk assessment and inform sustainable management strategies for agricultural and river-connected systems in tropical regions.

**Keywords:** *Environmental antimicrobial resistance; Sulfamethoxazole; Soil–water interactions; Climate-driven soil processes; Stable isotope*

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# Legacy Phosphorus and the Environmental Health of Agricultural Soils in South Korea

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**ABSTRACT**

South Korean agriculture has an extreme phosphorus (P) imbalance, with much greater amounts of phosphate fertilizer added to the land than is removed in crops. This imbalance has caused P to accumulate in soils to high concentrations throughout the nation. Reservoirs and rivers across South Korea are eutrophic and suffer from annually from toxic algal blooms, while dead zones are increasingly common in coastal areas around the country. South Korea uses a unique soil P test method – a modification of the Lancaster P test – which complicates comparison with other world regions. However, conversion of thousands of Lancaster P values from the Korean national soil inventory to Olsen P indicates that South Korean soils contain on average the highest soil test P levels in the world. As a result, most soils in the national inventory exceed recommended P levels for optimum crop growth, particularly for upland soils under plastic-film house agriculture. Estimation of the risk of P loss to water using break point analysis indicates that available P in most upland soils exceeds the point at which P leaching increases strongly. This value is comparable to the recommended soil test P levels for most crops, limiting opportunities to reduce environmental risk by drawing down legacy P. However, assessment by sequential fractionation, $^{31}$P NMR spectroscopy, and XANES spectroscopy indicates that the chemical nature of the accumulated P varies depending on soil pH and land use, offering opportunities for developing targeted drawdown strategies. Given the extremely high national P imbalance, widespread accumulation of legacy P, and pervasive eutrophication, South Korea must urgently develop novel long-term strategies to reduce agricultural P inputs and reduce legacy P while simultaneously maintaining crop productivity and improving soil and environmental health.

# Ligand-to-Metal Charge Transfer Driven Transformation of Ferrihydrite and its Effect on Arsenic Repartitioning

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**ABSTRACT**

Ferrihydrite, a poorly ordered metastable iron oxide, is closely associated with dissolved organic matter (DOM) in soils and sediments. Although sunlight-induced photoreductive dissolution of ferrihydrite via ligand-to-metal charge transfer (LMCT) process has been extensively studied, its potential impacts on mineralogical transformation and environmental behaviors of coexisting contaminants remain largely unknown. Here, we systematically investigated effects of environmental parameters (e.g., solution pH, $pO_2$ level, arsenic speciation and content) on ferrihydrite transformation with the representative DOM-oxalate under simulated solar irradiation. Results showed that oxalate-mediated LMCT process synchronously initiated Fe(II) production and solution deprotonation, the latter of which facilitated interfacial electron transfer-atom exchange (IET-$AE_{Fh\text{-}Fe2+}$) process among ferrihydrite and newly formed Fe(II). At pH 5.0-8.0, ferrihydrite was prone to transform into goethite due to appropriate degree of both $LMCT_{oxa}$ and IET-$AE_{Fh\text{-}Fe2+}$ processes, while it only underwent reductive dissolution at pH 3.0-5.0 or kept a steady state over pH 8.0. Increasing $pO_2$ level and arsenic content hampered the recrystallization of ferrihydrite, whereas the presence of As(III/V) also led to the formation of lepidocrocite with As(V) being more prominent. Additionally, chemical extraction and As *K*-edge EXAFS spectroscopy revealed that As was consecutively incorporated into the structures of goethite and lepidocrocite in the form of As(V) regardless of primary As speciation. These findings shed novel insights into low-crystalline iron oxide transformation and element migration driven by sunlight in natural environments.

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# Advancing Microplastics Research and Mitigation through Nuclear Science and Case Studies

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**ABSTRACT**

Microplastics are pervasive contaminants across environmental and food systems, threatening ecosystem integrity and human health. This talk outlines the Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture of International Atomic Energy Agency's (IAEA) coordinated response, which mobilizes nuclear and isotopic techniques, capacity building, and international collaboration to generate actionable evidence and practical solutions. The IAEA employs unique nuclear tools—such as isotope tracing, neutron activation, and radiation-assisted sample preparation—to advance source-to-sink understanding and harmonize measurements alongside conventional analytical workflows. Through its global networks, the IAEA supports method development, proficiency testing, and integrated monitoring that links microplastics surveillance with nutrient, contaminant, and antimicrobial resistance tracking. Beyond detection, the IAEA promotes radiation processing (gamma/electron beam) to enhance plastic circularity and reduce microplastic loads in wastewater and sludge. The presentation also highlights a case study, investigating micro-nanoplastics (MNPs) and phthalate esters (PAEs) in agricultural systems. Using lettuce as a model, the research combined fluorescence labeling, microscopy, transcriptomics, and metabolomics to examine uptake pathways and molecular responses to sub-microplastics (SMPs) and co-contamination with di(2-ethylhexyl) phthalate (DEHP). Key findings show that SMPs are absorbed and translocated within plants, altering gene expression and metabolism. Positively charged SMPs caused greater toxicity than negatively charged ones. Notably, DEHP exhibited antagonistic—not synergistic—effects, reducing SMP accumulation and alleviating oxidative stress and soil microbial disruption. The talk presents new evidence on microplastic fluxes in food webs, results from harmonization efforts and Member State case studies, and a forward agenda linking nuclear science, standardized monitoring, and circular economy solutions to measurable risk reduction. By integrating rigorous analytics with deployable technologies, the IAEA assists countries in translating science into effective policy and practice.

**Key Words:** micro-nanoplastics, plant, soil, environmental health

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# Isotopic Techniques to Assess the Fate of Antimicrobials and Implications for Antimicrobial Resistance in Agricultural Systems

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**ABSTRACT**

The fate of antimicrobials in farm ecosystems and the related risks of antimicrobial resistance (AMR) have attracted global attention. In our study, sulfamethoxazole (SMX) was selected as a model to systematically study its migration, transformation mechanisms, and AMR characteristics using various stable isotope techniques. First, Compound-Specific Isotope Analysis (CSIA) was used to determine the dual-element fractionation of 13C and 15N during degradation. This approach clarified the variations in natural degradation pathways and reaction mechanisms of SMX across different soils. Subsequently, a specifically synthesized 13C10-SMX was utilized as a tracer. Through isotope tracing, we measured the transfer and distribution of SMX in the soil-lettuce system, while also revealing its driving effects on the propagation of AMR. Furthermore, using Stable Isotope-Assisted Untargeted Metabolomics (SIAM), we tracked the 13C-label to identify both endogenous and exogenous metabolites of SMX within the complex plant matrix. Finally, using DNA-Stable Isotope Probing (DNA-SIP), we identified specific soil microbes and antibiotic resistance genes (ARG) stimulated by organic fertilizer that actively assimilate 13C-SMX. By linking environmental fate with microscopic metabolic mechanisms, this study constructs a comprehensive “Pollutant-Metabolite-Functional Microbe” network. These findings provide a robust scientific basis for the monitor, control, and risk assessment of antimicrobials and AMR in agricultural environments.

**Acknowledgments**

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# Synthesis and isotope analysis of labelled sulfamethoxazole to trace persistence and natural degradation in the field

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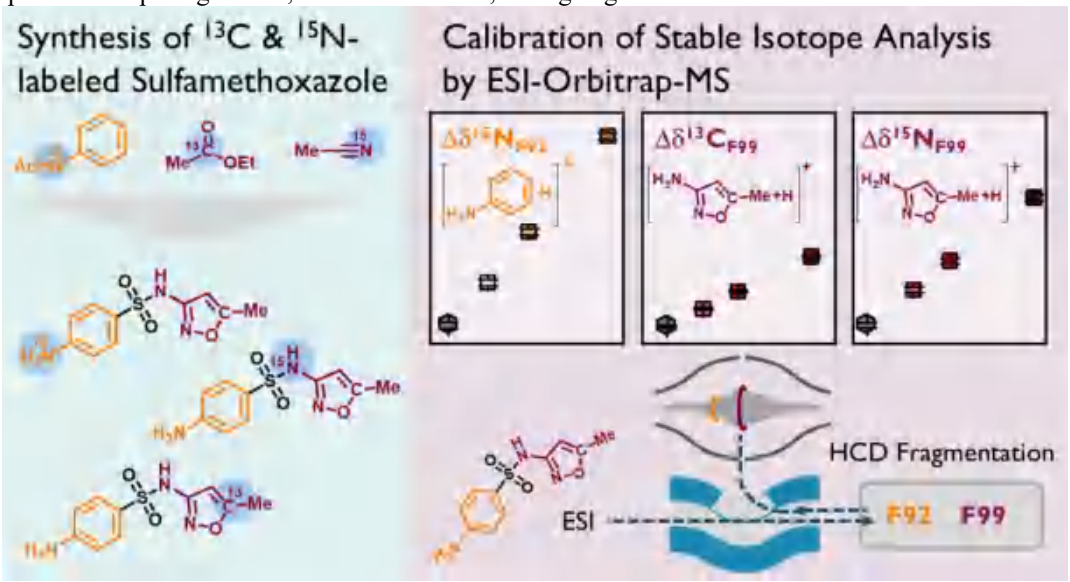
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## ABSTRACT

The widespread presence of pharmaceuticals, including the widespread antimicrobial sulfamethoxazole (SMX), in our aquatic environment raises important societal concerns. Stable isotope techniques offer two powerful avenues to study their fate and degradation. **First, isotope-labeled antimicrobials** can be applied in realistic field settings. This enables the distinction between previous contamination of the target antimicrobial and the freshly introduced label, and can trace the flux of stable isotopes into the biomass of actively degrading microorganisms. **Second, stable isotope analysis at natural abundance** offers unique insight into source fingerprinting. Changes in these isotope values are further an indicator of natural degradation, as they are the result of degradation-associated kinetic isotope effects. Both approaches can, therefore, deconvolve changes in concentrations that are caused by degradation from those changes that are brought about by repetitive application or remobilization.

**To support the first approach**, we synthesized fully $^{13}C$-labelled sulfamethoxazole (SMX) for a concerted effort within the CRP D15022_AMR of the International Atomic Energy Agency (IAEA), to study the fate of this antimicrobial in actual field experiments. In parallel, **in support of the second approach** we synthesized compound-specific References standards to enable electrospray ionization (ESI) Orbitrap mass spectrometry as novel approach for fragment-specific carbon and nitrogen isotope analysis ($Dd^{13}C$ and $Dd^{15}N$) of SMX at natural isotopic abundance. Fragment-specific isotope analysis relied on fragmentation of SMX ions in the collision cell, forming two fragment ions representing the aniline part (m/z = 92, F92) and the 3-amino-5-methylisoxazole ring (m/z = 99, F99) of SMX. References materials were prepared (i) through total synthesis of SMX from labelled precursors that resulted in specific positions labeled with $^{13}C$ and $^{15}N$, (ii) followed by the mixing of labeled SMX with SMX at natural abundance. The bulk isotope values of these in-house standards were determined by elemental analysis isotope ratio mass spectrometry and used for calibration of the ESI-Orbitrap method. Injecting standards directly into the Orbitrap resulted in 95% confidence intervals (CIs) 0.7‰ and 3.4‰ for $Dd^{13}C$ and $Dd^{15}N$ in F92, respectively, and 1.3‰ and 2.9‰ for $Dd^{13}C$ and $Dd^{15}N$ in F99 for quintuplicate measurement of standards. A proof-of-principle demonstration shows that this approach could indeed successfully quantify changes in fragment-specific isotopic signatures, $Dd^{13}C$ and $Dd^{15}N$, during degradation of SMX.

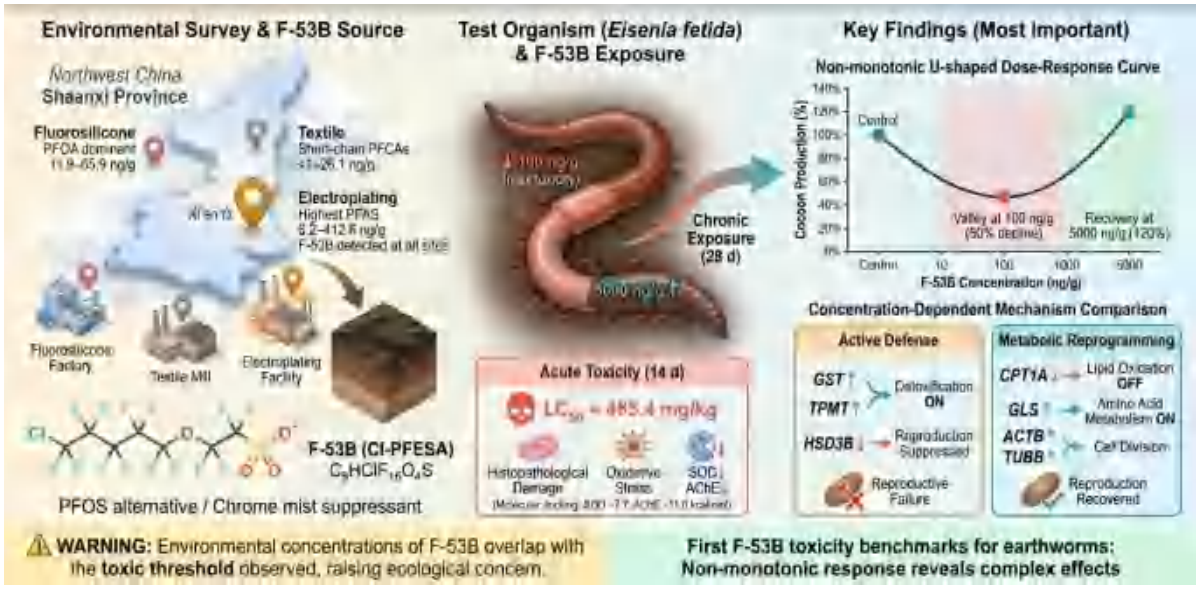


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# Non-monotonic Reproductive Toxicity of F-53B in Earthworm: Environmental Relevance from Northwest China Industrial Soils

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## ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are emerging contaminants of increasing global concern. However, PFAS contamination data for Northwest China remain limited, and ecotoxicological effects of emerging alternatives on soil organisms are largely unknown. This study addresses these gaps through systematic PFAS characterization across industrial parks in Shaanxi Province, China, combined with the first comprehensive toxicity assessment of the PFOS alternative F-53B (Cl-PFESA) in *Eisenia fetida*.

**Environmental Survey:** Soil sampling across three industrial sectors revealed distinct contamination profiles. Fluorosilicone manufacturing exhibited PFOA-dominated pollution (11.9–65.9 ng/g; >90% PFOA), textile finishing showed moderate short-chain perfluorocarboxylic acid contamination (<1–26.1 ng/g), and electroplating sites displayed the highest levels (6.2–412.6 ng/g), with PFOS and F-53B collectively accounting for >60% of total PFAS. F-53B was detected at all electroplating sites (10–70% composition), reflecting its widespread use as chromium mist suppressant.

**Toxicity Assessment:** Acute exposure (14 d) induced dose-dependent mortality with $LC_{50}$ of 465.4 mg/kg. Sublethal exposure caused significant histopathological alterations and oxidative stress. Molecular docking revealed stable F-53B binding to SOD (−7.7 kcal/mol) and AChE (−11.0 kcal/mol), corroborating observed enzyme inhibition.

Chronic exposure at environmentally relevant concentrations (10–5000 ng/g; 28 d) revealed non-monotonic reproductive toxicity. Cocoon production declined by 50% at 100 ng/g but recovered to 120% of controls at 5000 ng/g. Transcriptomic profiling identified concentration-dependent mode switching: "active defense" at 100 ng/g with detoxification upregulation (GST↑, TPMT↑) but reproductive suppression (HSD3B↓), versus "metabolic reprogramming" at 5000 ng/g featuring suppressed lipid catabolism (CPT1A↓, ACADVL↓), enhanced amino acid metabolism (GLS↑), and upregulated cytoskeletal proteins (ACTB↑, TUBB↑). Reproductive recovery may be associated with metabolic shifts favoring biosynthetic capacity.

**Ecological Significance:** The concentration eliciting maximum toxicity (100 ng/g) falls within ranges detected at electroplating sites, indicating current environmental F-53B levels may pose risks to soil invertebrates. This study establishes the first F-53B toxicity benchmarks for earthworms and reveals novel non-monotonic mechanisms challenging conventional dose-response assumptions.

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# Remediation of Prometryn-Contaminated Soil through Microbial-Phytoremediation Synergy: An Integrated Strategy for Soil Degradation Control and Sustainable Reclamation

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## ABSTRACT

In the context of intensifying agricultural production and escalating environmental challenges, soil degradation has emerged as a critical global issue threatening food security and ecosystem sustainability. China, as a major agricultural nation, relies significantly on chemical inputs including pesticides to maintain crop productivity. Among these, herbicides constitute the largest segment of the global pesticide market, with triazine herbicides like prometryn being widely adopted due to their broad-spectrum weed control, cost-effectiveness, and relatively low mammalian toxicity [1-2]. However, the persistent nature of prometryn in soil ecosystems poses substantial risks to non-target organisms and soil health. As a systemic and translocative herbicide, prometryn primarily functions by disrupting photosynthetic electron transport in plants, thereby inhibiting ATP synthesis and ultimately impairing cellular functions [3-4]. Beyond its intended phytotoxic effects, prometryn residues can accumulate in soils, leading to reduced microbial diversity, altered nutrient cycling processes, and long-term degradation of soil quality.

To address these challenges, this study investigates an integrated remediation approach combining microbial augmentation with phytoremediation—a strategy that holds particular promise for sustainable soil reclamation. We focused on the interaction between *Bacillus proteolyticus* strain 4-7, a plant-growth-promoting rhizobacterium with demonstrated biofertilizer potential [5], and alfalfa (*Medicago sativa L.*), a perennial leguminous forage renowned as the "King of Forages" for its exceptional soil-improving capabilities [6]. Alfalfa exhibits remarkable adaptability to stressed environments, with documented abilities to modify soil pH, enhance microbial activity, and facilitate contaminant immobilization [7-9]. The synergistic potential of combining these biological agents for remediating herbicide-contaminated soils represents an innovative approach to soil restoration that merits systematic investigation.

The experimental design employed soil artificially contaminated with prometryn at three environmentally relevant concentration gradients 0mg/kg,0.25mg/kg,and0.5mg/kg, reflecting both background and moderately contaminated agricultural scenarios. Three primary treatments were established: (1) prometryn-contaminated soil with alfalfa monoculture, (2) contaminated soil with both alfalfa and Bacillus 4-7 inoculant application, and (3) contaminated control soils without plants or microbial amendment. A comprehensive assessment protocol was implemented, analyzing changes in soil physicochemical properties (including pH, organic matter, total and available nitrogen, phosphorus, and potassium), key enzyme activities (catalase, urease, and sucrase) as indicators of microbial metabolic function, and microbial community structure through high-throughput sequencing approaches. This multi-faceted analytical framework enabled a holistic evaluation of remediation efficacy across chemical, biochemical, and biological dimensions of soil health.

The investigation yielded several significant findings that elucidate the mechanisms and effectiveness of this integrated bioremediation strategy:

(1) Soil Nutrient Dynamics and Fertility Enhancement: The combined Bacillus-alfalfa treatment exerted pronounced effects on soil nutrient status under prometryn stress. While organic matter content exhibited a gradual decline with increasing herbicide concentration—likely reflecting initial microbial stress—specific nutrients demonstrated optimized accumulation patterns at different contamination levels. Total phosphorus 0.35g/kg, total nitrogen 1.35g/kg, and nitrate nitrogen reached maximal concentrations at 0.25 mg/kg prometryn, suggesting that low-level contamination may initially stimulate certain nutrient mobilization processes. At 0.5 mg/kg prometryn, total potassium and ammonium nitrogen peaked, indicating the system's capacity to maintain potassium cycling and ammonium retention even under moderate stress. Notably, available phosphorus achieved its highest level at 1.0 mg/kg prometryn, revealing a potentially hormetic response where moderate contamination stimulates phosphorus solubilization mechanisms. Comparative analysis against control soils revealed statistically significant improvements: total potassium increased substantially ($P < 0.01$), ammonium nitrogen rose by 89.61%, and organic matter content enhanced by 55.62%. Simultaneously, soil pH decreased by 5.66% ($P < 0.01$), shifting toward more neutral conditions favorable for nutrient availability and microbial activity. When compared to alfalfa monoculture, the interactive treatment further boosted total potassium by 102.99% and organic matter by 22.79%, with total nitrogen increasing up to 164.86% in specific treatments. These findings collectively demonstrate that the plant-microbe partnership not only counteracts herbicide-induced nutrient depletion but actively enhances soil fertility parameters beyond what either component achieves independently.

(2) Soil Enzyme Activity and Biochemical Functionality: Enzymatic assays provided insights into the treatment effects on soil biochemical processes. During alfalfa germination, catalase activity—which decreased progressively with rising prometryn concentration in control soils—was effectively maintained in the interaction treatment, indicating improved oxidative stress mitigation. Urease activity, relatively stable in contaminated controls, showed significant enhancement following combined remediation, suggesting stimulated nitrogen transformation pathways. Most remarkably, sucrase activity not only increased substantially in treated soils but exhibited a positive correlation with prometryn concentration, implying that the remediation system may upregulate carbon cycling processes in response to contaminant challenge. These enzymatic responses collectively indicate that the Bacillus-alfalfa system preserves and even enhances the metabolic capacity of soil microbiota under herbicide stress, maintaining critical nutrient cycling functions that are often impaired in degraded soils.

(3) Microbial Community Restructuring and Functional Recovery: Microbial diversity analysis revealed temporal dynamics in community responses. Initial contamination stages maintained relatively high diversity, but prolonged prometryn exposure under natural attenuation reduced diversity and compromised ecosystem functions. Alfalfa planting alone significantly reversed this trend, restoring microbial richness and evenness compared to natural attenuation controls. The addition of Bacillus 4-7 introduced further modulation, increasing community variability but also enhancing the relative abundance of key functional taxa. Proteobacteria and Sphingomonas emerged as consistently dominant groups across treatments, with the latter—known for its aromatic compound degradation potential—showing particular enrichment in remediation groups. Statistical analysis revealed significant positive correlations between Sphingomonas abundance and soil $NO_3^-$-N and available potassium $r=0.69, P<0.05$, suggesting functional coupling between this bacterial group and nutrient mobilization processes. Venn diagram analysis indicated that phytoremediation treatments reduced the number of unique operational taxonomic units (OTUs) while increasing shared community members, promoting a more homogeneous and functionally integrated microbial assemblage. This community restructuring appears driven by altered rhizosphere chemistry, with remediation treatments creating nutrient conditions that selectively enrich beneficial bacterial lineages while suppressing non-functional or stress-sensitive taxa.

The implications of these findings extend beyond prometryn remediation to broader applications in soil reclamation practice. The demonstrated capacity of this plant-microbe system to simultaneously address multiple aspects of soil degradation—contaminant stress, nutrient imbalance, pH extremes, and microbial dysfunction—aligns with the integrated approach needed for effective soil restoration. Specifically, the treatment's ability to enhance potassium and nitrogen retention while reducing pH addresses common limitations in degraded agricultural soils. The stimulation of enzyme activities and functional microbial taxa suggests restored biochemical cycling capacity. Perhaps most significantly, the promotion of a more homogeneous, functionally coherent microbial community represents a shift toward more resilient soil ecosystems capable of maintaining functions under stress.

In conclusion, this study provides compelling evidence that the synergistic interaction between *Bacillus proteolyticus* 4-7 and alfalfa constitutes an effective, ecologically sound strategy for remediating prometryn-contaminated soils and mitigating associated degradation processes. The approach enhances soil fertility parameters, preserves critical enzymatic functions, and restores functional microbial community structure through targeted enrichment of beneficial taxa. These findings advance our understanding of plant-microbe partnerships in contaminated environments and offer a practical, sustainable methodology for soil reclamation that aligns with contemporary priorities in sustainable agriculture and environmental management. Future research should explore field-scale applications, long-term stability of observed improvements, and potential extensions to other herbicide classes and degradation scenarios to further validate and expand the utility of this promising bioremediation strategy.



Figure 1 Heatmap of species-environment factor correlations after interaction between fungicides 4-7 and alfalfa

## Acknowledgments

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# Antibiotic resistance at environmental multi-media interfaces through integrated genotype and phenotype analysis

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## ABSTRACT

Antibiotic resistance is currently an unfolding global crisis threatening human health worldwide. While antibiotic resistance genes (ARGs) are known to be pervasive in environmental media, the occurrence of antibiotic resistance at interfaces between two or more adjacent media is largely unknown. Here, we designed a microcosm study to simulate plastic pollution in paddy soil and used a novel method, stimulated Raman scattering coupled with deuterium oxide ($D_2O$) labelling, to compare the antibiotic resistance in a single medium with that at the interface of multiple environmental media (plastic, soil, water). Results revealed that the involvement of more types of environmental media at interfaces led to a higher proportion of active resistant bacteria. Genotypic analysis showed that ARGs (especially high-risk ARGs) and mobile genetic elements (MGEs) were all highly enriched at the interfaces. This enrichment was further enhanced by the co-stress of heavy metal (arsenic) and antibiotic (ciprofloxacin). Our study is the first to apply stimulated Raman scattering to elucidate antibiotic resistance at environmental interfaces and reveals novel pathway of antibiotic resistance dissemination in the environment and overlooked risks to human health.

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# Pollution characteristics, sources and risk assessment of per- and polyfluoroalkyl substances (PFASs) in river water, sediments, soils of the Inner Mongolia Section of the Yellow River

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFASs) are persistent contaminants that can accumulate in aquatic and terrestrial compartments, yet integrated evidence across water–sediment–soil continua remains limited for major river basins. This study investigated 17 PFASs in surface water, riverine sediments and riparian soils along the Inner Mongolia reach of the Yellow River during wet and dry seasons, aiming to characterize multi-media occurrence, seasonal patterns and potential sources, and to evaluate ecological and human health risks. PFASs were ubiquitous in all media and exhibited pronounced spatial and seasonal heterogeneity. In surface water, $\Sigma_{17}$PFASs ranged from 11.0–68.5 ng/L in the wet season and 9.5–95.3 ng/L in the dry season, indicating higher overall contamination during low-flow conditions; perfluorooctanoic acid (PFOA) and perfluorobutyric acid (PFBA) were dominant compounds. Sediments contained 185.9–723.3 pg/g dry weight (dw) $\Sigma_{17}$PFASs, with PFOA contributing 23.6–35.6%. Riparian soils showed 94.6–1071.6 pg/g dw $\Sigma_{17}$PFASs, dominated by long-chain PFASs (40.44–45.88%). The relative contribution of PFAS precursors in soils was higher in the wet season (28.39%) than in the dry season (17.01%), implying enhanced terrestrial inputs and transformation potential under rainy conditions. Source apportionment indicated mixed anthropogenic influences, with major contributions linked to aqueous film-forming foams (AFFF), metal plating, product manufacturing and other urban–industrial activities, alongside inputs associated with agricultural practices and consumer products. Risk assessment revealed that sedimentary PFOA posed the highest ecological concern (risk quotient, RQ=0.225, medium risk), whereas human health risks via drinking water and grain intake were low (hazard quotient, HQ<0.2). These findings indicate that PFASs in sediments from certain sections of the Yellow River in Inner Mongolia pose ecological risks to the environment. It is recommended that industrial source control and process barrier measures be prioritized in hotspot areas within the Yellow River basin.

**Acknowledgments**

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# Persulfate activation by Schwertmannite degrading phenanthrene in soil

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Keywords: phenanthrene, persulfate, Schwertmannite, *Brassica parachinensis*

## ABSTRACT

**Introduction**

Phenanthrene contamination in soil poses a serious threat to agroecosystems and food safety. While persulfate-based advanced oxidation processes have garnered significant attention for efficiently degrading organic pollutants—particularly with iron-based catalysts like zero-valent iron and $Fe^{2+}$—this study innovatively employs a Schwertmannite-activated persulfate system. The research aims to: (1) systematically evaluate the degradation efficiency of phenanthrene in soil, and (2) investigate the mechanism by which this system inhibits phenanthrene uptake in crops, using *Brassica parachinensis* as a model. This work is expected to provide a novel strategy for remediating phenanthrene-contaminated farmland, one that simultaneously removes pollutants and mitigates food safety risks.

**Methods**

Schwertmannite was synthesized according to the method of Liu et al.[2]. A pot experiment was conducted, in which the concentrations of Schwertmannite, persulfate, and phenanthrene were set at 1 g/kg, 200 mg/kg, and 20 mg/kg, respectively. Soil samples were collected every five days. The contents of phenanthrene in the soil extracts were analyzed by gas chromatography-mass spectrometry.

**Results**

In this study, we explored the degradation efficiency of phenanthrene in soil using a Schwertmannite-activated persulfate system and evaluated the ability of the treatment to limit phenanthrene uptake and accumulation in *Brassica parachinensis*. As shown in Fig.1, the system which added schwertmannite and persulfate together achieved a phenanthrene removal rate of 86.2% after 5 days, while all other treatments were lower than 31.9%. The concentration of phenanthrene in *Brassica parachinensis* exhibited notable variations across different treatments (Fig.2). The lowest phenanthrene accumulation across all plant tissues was consistently observed in the treatment where both persulfate and Schwertmannite were applied together.

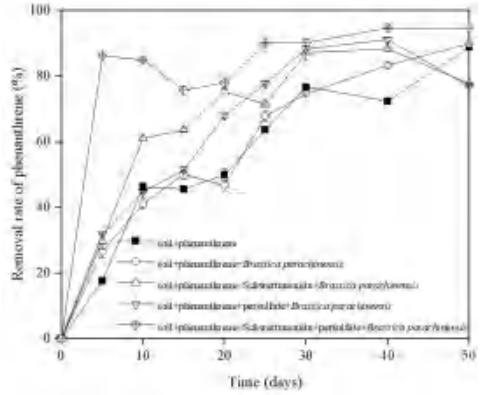



Fig.1. Dynamics of Phe under different treatments

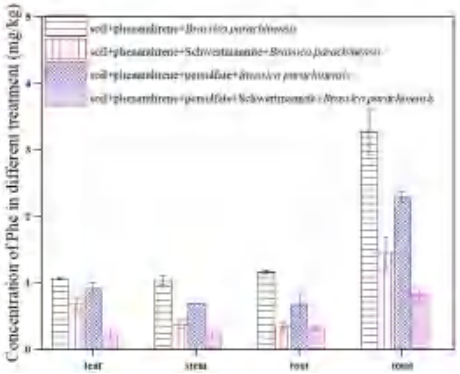



Fig.2. Migration of Phe in leaf, stem, and root of Bok choy

**Conclusion**

The combined application of Schwertmannite and persulfate rapidly degraded phenanthrene in the contaminated soil, thereby effectively preventing its uptake and accumulation by *Brassica parachinensis*.

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# Fate of Di(2-ethylhexyl) Phthalate (DEHP) in Agricultural Soil: The Role of Environmentally Characteristic Microplastics

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## ABSTRACT

The extensive use of agricultural plastic films has led to increasing contamination of farmland soils with emerging pollutants such as microplastics (MPs) and plasticizers. However, the environmental behavior of these co-occurring pollutants and their interactions remain poorly understood. In this study, we investigated the environmental behavior of the plasticizer Di(2-ethylhexyl) phthalate (DEHP) in two typical Chinese agricultural soils (Chao soil and red soil), along with the effects and potential mechanisms of environmentally relevant polyethylene microplastics (PE-MPs) on the fate of DEHP. Using $^{14}$C-isotope tracing techniques, we first examined the mineralization, extractable residues, and non-extractable residues (NERs) of DEHP in aerobic farmland soils. Our results demonstrate that DEHP's environmental behavior is governed by soil properties (e.g., pH, organic matter, and clay content) and its inherent characteristics. In active soils, DEHP showed high mineralization and extractable residues, with relatively stable non-extractable residues (NERs), indicating significant short-term environmental risk. Over time, however, the locked NERs showed instability, suggesting potential long-term environmental risks. Compared to chao soil, red soil exhibited lower mineralization and higher extractable residues of DEHP, indicating higher bioavailability and persistence of DEHP in red soil, which may pose greater environmental risks. Furthermore, we explored the impact of PE-MPs on the environmental fate of DEHP and the possible mechanisms involved. Critically, the presence of PE-MPs significantly altered DEHP's fate. Sorption-desorption experiments revealed that PE-MPs have a higher affinity for DEHP (log Kd: PE-MPs > red soil > chao soil). In soil, PE-MPs reduced DEHP mineralization and NER formation while increasing its extractable residues, thereby enhancing bioavailability and immediate environmental risk. Notably, PE-MPs influenced DEHP fate primarily in sterilized soils and delayed the formation of stable, locked NERs. This study provides novel insights into the co-fate of MPs and plasticizers, revealing that MPs can remobilize aged organic pollutants and increase their bioavailability. These findings are crucial for developing scientifically sound risk assessment frameworks and effective pollution control strategies for composite pollution in agricultural ecosystems.

**Key words:** Microplastics; Plasticizers; Non-extractable residues (NERs); $^{14}$C isotope tracing

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# Contrasting effects of arsenic and cadmium on PFAS sorption and transport in soils: Mechanistic insights and mathematical models

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**ABSTRACT**

An in-depth understanding of the sorption behaviors of per- and polyfluoroalkyl substances (PFAS) in soil is essential to assess their environmental risks accurately. Due to chemical industry production and waste treatment, co-contamination soil of heavy metals (HMs)-PFAS has become a public concern worldwide. This study investigated soil sorption and transport behaviors of PFAS including perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), and perfluorohexanesulfonic acid (PFHxS) under coexisting As5+/Cd2+.

Combining batch experiments, column tests, and Hydrus-1D modeling, the sorption isotherms and transport dynamics of PFAS were examined. PFAS sorption affinity followed the order: PFOS > PFOA > PFHxS, while the opposite order was observed for desorption and transport rates. A multiple linear regression (MLR) model was developed to predict the soil sorption of PFOS. Validation results demonstrated that this model could effectively predict the distribution coefficients ($K_d$) of PFOS based on soil organic carbon (OC), silt, clay, and Fe oxide contents, exhibiting a strong predictive ability ($r^2 = 0.942$, $p < 0.001$). In raw soils, $As^{5+}$ and $Cd^{2+}$ influence three anionic PFAS sorption primarily by altering the electrostatic and hydrophobic interactions between soil components and PFAS. The $K_d$ values of PFOS tend to rise with increasing $Cd^{2+}$ concentration but decline with increasing $As^{5+}$ concentration. In contrast, HMs have a relatively minor influence on the sorption of PFOA and PFHxS. Subsequently, a nonlinear model was constructed for the first time to quantify the impact of HMs on PFAS sorption, achieving exceptional prediction accuracy when applied to both experimental data from this study and literature data. In column tests, the breakthrough curves (BTC) of PFOA and PFHxS are generally symmetric, but the BTC of PFOS displays a nonideal transport. Critically, $As^{5+}$ accelerated PFOS transport by 9.4-34.9% through pH-induced repulsion and site competition, while $Cd^{2+}$ enhanced PFOS retention by 61.6-86.8% through electrostatic attraction and cation bridging. Furthermore, multiple PFAS transport datasets were used to validate a mathematical model incorporating advection-dispersion and chemical nonequilibrium sorption, and the model was applied for the first time to simulate the PFAS transport in the saturated zone affected by HMs. Long-term simulation (50 years) showed that $As^{5+}$ accelerates PFOS migration to groundwater (5 m), whereas $Cd^{2+}$ restricts its penetration to a depth of 0.2 m. Given weak sorption, PFOA and PFHxS quickly leach downward and threaten groundwater safety within 10 years. This study developed predictive frameworks for PFAS sorption, transport, and risk assessment in industrial sites, enhancing priority management and remediation strategies based on the characteristics of co-contaminants to protect the soil environment and groundwater sources.

**Keywords**

PFAS-HMs co-contamination; Batch and column methods; Interaction mechanisms; Mathematical model; Long-term transport.

**Figures**



**Fig. 1.** Mechanisms and mathematical model analysis for PFAS sorption in soils under coexisting HMs.

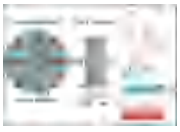


**Fig. 2.** PFAS transport in saturated soils and modeling via Hydrus-1D.

**Acknowledgments**

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# Spatiotemporal pattern and Mitigation Potential of Carbon Emissions from Ex-Situ Thermal Desorption for Contaminated Sites in China

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**ABSTRACT**

Ex-situ thermal desorption (ESTD) has been widely applied in the remediation of organically contaminated sites in China due to its high treatment efficiency. However, this technology relies on continuous heating and is therefore highly energy-intensive, attracting increasing attention to its carbon emissions. To identify the key environmental burden of soil remediation and support green and sustainable remediation, this study developed a full-process carbon accounting framework for ESTD based on engineering practices in China. Based on data from 210 ESTD cases from 2011 to 2025 in China, the primary sources, spatiotemporal patterns, and future mitigation potential of carbon emissions from ESTD were systematically analyzed. Results showed that ESTD consumed 2200–4300 MJ per cubic meter of soil treated, and the thermal treatment stage accounted for 83.77% of total carbon emissions. Over the past 15 years, ESTD in China generated a total of 1.98 Mt $CO_2$. Temporally, national carbon emissions of ESTD experienced four stages: initial development, rapid expansion, high-level fluctuation, and gradual stabilization. Spatially, high-emission areas were concentrated along the Yangtze River Economic Belt and expanded from the middle and lower reaches to the upper reaches. Mitigation potential analysis further indicated marked interprovincial differences in optimal pathways. Under the combined province-specific optimal pathways, the maximum national mitigation rate of ESTD could reach 16.86% by 2035. These findings suggest that the low-carbon transition of ESTD can be better realized through region-specific strategies that consider provincial energy structures and technology suitability. This study provides important support for ensuring the safe use of soil resources and promoting the green and sustainable soil remediation.

# Microbial Communities and Metabolic Potential for Reductive Debromination of 2,4,6-Tribromophenol in Deep-Sea Cold Seep Sediments

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**ABSTRACT**

Bromophenols are among the most common naturally synthesized compounds in the marine environment. Deep-sea cold seeps are potential reservoirs of microorganisms capable of degrading halogenated organic pollutants, such as 2,4,6-tribromophenol (TBP). This study investigated the microbial communities and their functional potential for TBP reductive debromination in cold seep sediments from the South China Sea. Anaerobic enrichments with TBP as the sole electron acceptor were established from sediment samples at different depths (0-150 cm). All enrichments showed debromination activity, with the 150 cm-depth culture exhibiting the highest efficiency, completely converting TBP to phenol. Metagenomic analysis revealed Pseudomonadota and Bacillota as the dominant phyla. A total of 23 high-quality metagenome-assembled genomes (MAGs) carrying reductive dehalogenase (*rdhA*) genes were recovered, all belonging to the phylum Bacillota. The most active culture also had the highest *rdhA* gene abundance and diversity. Genomic context analysis revealed structurally complete *rdh* gene clusters in several MAGs. Metabolic profiling of high-quality MAGs indicated a universal dependence on the cobalamin salvage pathway, employing BtuBFCD transporters and adenosylcobinamide-phosphate synthase, as they lack a complete *de novo* biosynthesis route. Complementary research demonstrated that nutrient optimization (e.g., lactate with yeast extract) significantly enhanced TBP degradation and enriched a key novel dehalogenator, Bin3 (Peptococcaceae), which harbored multiple, expressed *rdhA* genes. Our findings confirm the presence of diverse and novel dehalogenating microorganisms in cold seeps, highlighting their ecological role and potential application in bioremediation.

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# Microbial reductive dehalogenation of emerging organohalides and its application in bioremediation

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**ABSTRACT**

Emerging organohalides, due to their persistence and lipophilic-hydrophobic characteristics, have become a significant challenge for site remediation in China. Traditional physicochemical remediation methods face limitations in terms of efficiency and sustainability, especially at industrial sites, where less disruptive and long-term stable remediation strategies are needed. Based on this, the present study developed an *in situ* microbial reductive dehalogenating remediation method and conducted a systematic investigation from three aspects: (1) Organohalide-respiring bacteria (OHRB) collection; (2) functional enhancement, and (3) engineering applications. Firstly, a dehalogenating respiratory strain collection was established by screening various environmental sources, including black-odor water bodies, landfills, salt lakes, and nearshore sediments, revealing the distribution characteristics of organohalides and their *in situ* transformation patterns in contaminated environments. Secondly, to enhance microbial activity, strategies such as growth promoters, interspecies interactions regulation, and habitat optimization were explored, effectively improving the efficiency of microbial reductive dehalogenating remediation. Finally, this technology was applied at typical polluted sites in Suzhou, Taizhou, and Shaoguan, demonstrating excellent remediation performance. This study provides a theoretical basis and technical pathway for the efficient bioremediation of emerging organohalides.

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# Soil Organic Carbon Prediction Based on Vis–NIR Spectral Classification Data Using GWPCA–FCM Algorithm

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**ABSTRACT**

Soil visible and near–infrared reflectance spectroscopy is an effective tool for the rapid esti- mation of soil organic carbon (SOC). The development of spectroscopic technology has increased the application of spectral libraries for SOC research. However, the direct application of spectral libraries for SOC prediction remains challenging due to the high variability in soil types and soil–forming factors. This study aims to address this challenge by improving SOC prediction accuracy through spectral classification. We utilized the European Land Use and Cover Area frame Survey (LUCAS) large–scale spectral library and employed a geographically weighted principal component analy- sis (GWPCA) combined with a fuzzy c–means (FCM) clustering algorithm to classify the spectra. Subsequently, we used partial least squares regression (PLSR) and the Cubist model for SOC predic- tion. Additionally, we classified the soil data by land cover types and compared the classification prediction results with those obtained from spectral classification. The results showed that (1) the GWPCA–FCM–Cubist model yielded the best predictions, with an average accuracy of R2 = 0.83 and RPIQ = 2.95, representing improvements of 10.33% and 18.00% in R2 and RPIQ, respectively, compared to unclassified full sample modeling. (2) The accuracy of spectral classification modeling based on GWPCA–FCM was significantly superior to that of land cover type classification modeling. Specifically, there was a 7.64% and 14.22% improvement in R2 and RPIQ, respectively, under PLSR, and a 13.36% and 29.10% improvement in R2 and RPIQ, respectively, under Cubist. (3) Overall, the prediction accuracy of Cubist models was better than that of PLSR models. These findings indicate that the application of GWPCA and FCM clustering in conjunction with the Cubist modeling technique can significantly enhance the prediction accuracy of SOC from large–scale spectral libraries.

**Keywords:** soil spectroscopy; LUCAS; GWPCA; FCM

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# A Novel Sample Selection Strategy for Instance-based Transfer Learning in Local Soil Organic Carbon Estimation

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**ABSTRACT**

Soil organic carbon (SOC) is a critical indicator of soil health and carbon cycling, essential for sustainable agricultural development and climate change mitigation. Visible near-infrared reflectance spectroscopy (vis-NIR) technology combined with machine learning models has shown potential for rapid and accurate SOC prediction. However, due to significant spatial heterogeneity in SOC distribution across different regions, global models based on soil spectral libraries (SSLs) often lack sufficient generalization capability for local applications. To address this challenge, we propose an innovative sample selection framework for instance-based transfer learning, KNN-FRSS, a forward recursive sample selection method combined with K-nearest neighbor algorithm. This framework identifies the most representative samples from the SSL for the target region using a two-step process: step 1: preliminary selection by local similarity metric, and step 2: precise selection by forward recursive sample selection mechanism, thereby enhancing the adaptability of cross-regional SOC modeling. We employed three predictive models (1D-CNN, Cubist, and PLSR) to evaluate the transferability of the KNN-FRSS strategy in cross-region modeling. In addition, we compared the performance of KNN-FRSS with another sample selection method (RS-LOCAL-v2.0) and feature-based transfer learning approach. These transfer learning methods were evaluated across four distinct regions. The results indicate that all transfer learning methods improved model predictive accuracy in four study regions. Notably, the combination of KNN-FRSS with the 1D-CNN model consistently outperformed the others. Compared to the best-performing models built using local data, this combined approach achieved an improvement in $R^2$ranging from 3% to 26%, and a reduction in RMSE by 12.82% to 43.4%. Finally, this study provides a feasible path to enhance the effectiveness of transfer learning in soil spectral modeling, and provides methodological support for rapid and high-accuracy SOC prediction across diverse geographic regions.

**Keywords:** transfer learning, SOC estimation, soil spectral library, sample selection

# Design of effective materials to collaborate with microorganisms in reductive remediation of chlorinated organic pollutants

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**ABSTRACT**

Chlorinated Organic Pollutants (COPs), due to their strong persistence, bioaccumulation, and carcinogenicity, have become a major challenge in global pollution control. Traditional chemical reduction techniques and microbial dechlorination methods, each with their own limitations, struggle to achieve efficient remediation of COPs alone. In recent years, the bio-abiotic synergistic dechlorination strategy, by integrating the advantages of abiotic catalysis and microbial metabolism, has demonstrated groundbreaking application potential. Current research primarily focuses on empirical optimization of material synthesis and its enhancement of microbial communities, lacking in-depth exploration of rational material design. Nature contains materials that promote biological dechlorination, including humus, protein-containing organic materials, and iron minerals. These naturally evolved systems over millions of years provide "natural wisdom" insights for the field of pollution remediation. Currently, nano-zero-valent iron materials are widely used in reductive dechlorination. CMC were used to enhance the stability of nZVI materials; then novel CMC-FeS@biochar was developed using biochar as carrier of iron materials to enhance the electron transfer and protect the stability of the iron materials; Furthermore, ball milling method was applied to both micro iron and pyrite to enhance their reductive ability by reducing the particle size and improving the surface activity at the same time. For improving the selectivity of the iron materials, sulfidation and nitridation were applied to change the surface properties of the iron materials, furthermore, biochar was also added as carrier to enhance the selectivity and reactivity at the same time. Finally, CMC-FeS@biochar was used for a bio-chem dechlorination process; nZVI, S-nZVI, nFe/Ni and ball milled Fe0/FeS2 was compared on their ability to enhance the microbial dechlorination; and Synergetic effect of nZVI@BMPC and sodium lactate as an external nutrient was proved to be able to achieve complete 2,4,6-trichlorophenol degradation by anaerobic sludge acclimated culture.

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# Anaerobic biochemistry at the core of reductive dehalogenation in soil and groundwater

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**ABSTRACT**

Many halogenated aromatics have been detected as contaminations in soil and groundwater, including halogenated alkenes, alkanes, aromatics and polyaromatics, some of which are highly persistent and toxic. Several organisms have been described to transform halogenated contaminants via different dehalogenation pathways. Such pathways can lead to different dehalogenation extents depending on the dominating microorganisms. In this talk I summarize our work on the biochemistry in Dehalococcoides, Dehalogenimonas, Dehalobacterium and Dehalobacter species, all able to reductively dehalogenate halogenated compounds but with important differences in the pathways and kinetics. We explore the underlying biochemistry that leads to such differential behavior to understand the processes and to be able to design a rational remediation strategy. This led to the identification of respiratory chain architectures, subunit compositions of respiratory complexes, cofactor compositions, and membrane-soluble mediators. However, we still see proteins within such dehalogenating systems which we cannot functionally describe. We now have indications that different electronic properties in the different respiratory chains lead to different enzyme mechanisms and eventually to different catalytic properties. This has major implications for the selection of treatment and enrichment conditions in situ.

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# The Marine Environment as a Rich Source of Diverse Anaerobic Organohalide-Respiring Bacteria

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**ABSTRACT**

Organohalogen compounds are widely distributed in the marine environment as a source of both anthropogenic pollution and natural production.: polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs) and brominated flame retardants are common anthropogenic contaminants of aquatic sediments, while a great variety of natural organobromine compounds are produced by sponges and other organisms. Cleavage of the carbon-halogen bond is a critical step in degradation of organohalides and the natural organohalogen cycle. Organohalide-respiring bacteria, which utilize organohalides as electron acceptors for energy conservation, play an important role in the global halogen cycle. They have been identified from bacteria phyla with a wide range of halogenated substrates and can be classified as obligate or facultative depending on whether organohalide respiration is their sole energy gaining metabolism. We have enriched and isolated diverse organobromide-respiring bacteria from different marine habitats, including organohalide-contaminated sediments, pristine sites, as well as marine sponges. These bacteria utilize both organohalides and sulfate as electron acceptors for energy conservation. Reductive dehalogenase (RDase) genes and the capacity for organohalide respiration were widely distributed in members of marine *Pseudomonadota*. Novel debrominating members of the *Desulfovibrionaceae* and *Desulfuromonadaceae* families were isolated from different estuarine and marine sediments. In contrast, organobromine-rich sponges appear to provide a specialized habitat for organohalide-respiring microbes with different *Desulfobacteraceae* species responsible for reductive dehalogenation in geographically widely distributed sponge species (Atlantic, Pacific and Indian Oceans and the Mediterranean) indicating a cosmopolitan distribution. The physiology and dehalogenation range of these two bacteria were investigated, and genomes are sequenced and analyzed for their metabolic potential. The genes relevant to reductive dehalogenation were further studied to extend our knowledge on the diversity of organohalide respiration. The identification of diverse bacteria capable of organohalide respiration through functional assays and dehalogenase gene analysis extends our knowledge of their extensive distribution and diversity in the marine environment. The prevalence and diversity of *rdhA* genes in various isolates and metagenomes indicates that organohalide respiring potential is widely distributed in marine habitats. Dehalogenating members of the *Desulfovibrionaceae*, *Desulfuromonadaceae* and *Desulfobacteraceae* bacteria appear to play an important role in natural organobromide cycling with major impact on the fate of organohalide pollutants in the marine environment.

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# Microbial defluorination of PFASs by native consortia enriched from PFASs and CAHs co-contaminated sites

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## ABSTRACT

This study investigated the biodegradation and defluorination potentials poly- and perfluoroalkyl substances (PFASs) by microbial communities enriched from soils collected at industrial sites contaminated with PFASs compounds. Specifically, the aerobic biodegradation of 6:2 FTS and subsequent anaerobic biotransformation of representative perfluorinated compounds, including TFA, PFOA, and HFPO-DA, were evaluated.

In the aerobic biodegradation of 6:2 FTS, an enriched microbial culture (SXC01) achieved ≥99.5% degradation of 6:2 FTS removal at initial concentrations of 0.5–5 mg/L within 14 days under sulfur-limiting aerobic conditions. The dominant strain, *Brucella anthropi* SX009, isolated from SXC01, degraded >99% of 6:2 FTS within 60 h by utilizing it as an alternative sulfur source and achieving 13% defluorination. Metabolite profiling identified 11 transformation products, including 6:2 FTCA, 6:2 FTUCA, 5:3 FTUCA, 5:3 FTCA, and terminal products PFHxA and PFHpA, indicating a stepwise oxidative chain-shortening pathway. The accumulation of 6:2 FTUCA suggests its further degradation may be rate-limiting, while the higher yield of PFHxA compared to PFBA supports the dominance of the 5:2 sFTOH degradation route. Integrated metatranscriptomic and transcriptomic analyses revealed significant upregulation of genes involved in desulfonation (e.g., *ssuEADCB*, *cysI*, *sbp*, *iscS*), defluorination (e.g., *ladA*, *dehH*, *crcB*, *dhaA*), and Fe–S cluster assembly (*suf* operon), together with increased expression of α/β-hydrolases, dehydrogenases, and oxidoreductases. Molecular docking further confirmed favorable binding of 6:2 FTS within hydrophobic or semi-polar active pockets, supporting their catalytic roles in fluorotelomer transformation.

In the anaerobic microcosm study, the defluorination of TFA, PFOA, and HFPO-DA were evaluated in 10 months of incubation experiments. The defluorination ratios of TFA, PFOA, and HFPO-DA reached 3.32%, 3.46%, and 2.15%, with their corresponding removal efficiencies of 8.03 ± 3.03%, 13.52 ± 4.96%, and 2.38 ± 0.49%, respectively. Microbial biotransformation intermediates, including TFA and PFA, were verified, and PFOA-derived metabolites PFHxA and PFHpA accumulated to 0.21 and 4.14 μg/L. Co-occurrence network analysis based on full-length PacBio amplicon sequencing showed that microbial functional modules were mainly composed of *Bacteroidetes*, *Nitrospirae*, *Acidobacteria*, and *Chloroflexi*, suggesting their involvement in anaerobic PFAS transformation.

Collectively, these findings demonstrate that indigenous microbial consortia from PFASs co-contaminated sites possess condition-dependent metabolic networks that enable highly efficient fluorotelomer degradation under sulfur limiting conditions. They also reveal that these consortia can mediate measurable anaerobic defluorination of fully perfluorinated compounds, providing a mechanistic basis for potential *in situ* bioremediation of PFASs in groundwater and soil.

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# Mapping the Co-Occurrence of Organohalides and Microbial Dehalogenation: A Microbial Biochemistry Framework for One Health

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**ABSTRACT**

Organohalides are ubiquitous and persistent contaminants. Despite their widespread presence, our understanding of their global distribution, the microbial capacity for their degradation across diverse habitats, and the true associated risks—particularly from mixtures and in specific environmental contexts—remains fragmented.

We first characterized the actual contamination status of 32 COPs across diverse habitats in China, revealing their widespread occurrence with hotspots linked to anthropogenic activities. Simultaneously, using global soil metagenomes and a curated dehalogenase database, we mapped the biogeography of microbial dehalogenation traits and taxa, demonstrating that the potential for microbial dehalogenation is also widespread, reflecting the global distribution of these compounds. As the organohalide-degrading bacteria was usually hard to isolate and culture, we established a new method which integrates anaerobic culture and single-cell Raman sorting under environmental stress, enabling the efficient isolation and cultivation of functional anaerobes. Mechanistic insights from our work highlight how microbial reductive dehalogenation, a key anaerobic pathway, is intricately coupled with other biogeochemical cycles (e.g., methanogenesis), driven by complex interspecies interactions (e.g. metabolic exchange, electron transfer). Conventional single-pollutant assessments significantly underestimate the ecotoxicological risk posed by COP mixtures. This synergistic risk is particularly pronounced in anaerobic/flooded habitats (like wetlands and paddy fields), where combined COP toxicity presents moderate to high threats to sediment-dwelling organisms, potentially disrupting vital biogeochemical processes including carbon cycling.

Collectively, our findings underscore the complex interplay between pollution, microbial ecology, and environmental conditions in shaping the impact of organohalides. This integrated perspective is vital for developing monitoring, refined risk assessment frameworks, and targeted microbial bioremediation strategies under the ‘One Health’ concept.

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# Stimulating Feammox-Associated Microbial Communities in Iron-Rich, Acidic Sediments from AFFF-Impacted Sites to Promote PFAS Defluorination

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFAS) are persistent and bioaccumulative contaminants widely used in industrial and consumer products, posing substantial risks to ecosystems and human health. Feammox, the anaerobic oxidation of ammonium ($NH_4^+$) coupled with ferric iron (Fe(III)) reduction, is a microbial process that occurs naturally in acidic and iron-rich soils and sediments. Microorganisms associated with Feammox have recently been recognized for their potential involvement in the transformation of perfluoroalkyl acids (PFAAs).

This study evaluates the feasibility of stimulating Feammox reactions and enhancing the activity of Feammox-associated bacterial groups through the addition of $NH_4^+$ and Fe(III) to sediments collected from acidic, iron-rich sites impacted by aqueous film-forming foams (AFFF). Both batch incubations and column experiments were conducted to assess microbial and geochemical responses under static and flow-through conditions that reflect environmental processes more realistically. Quantitative PCR was used to quantify Feammox-related microorganisms and to monitor dehalogenase and fluoride-ion transporter genes. Microbial community dynamics were characterized through 16S rRNA gene sequencing.

The results indicate that supplying Fe(III) and $NH_4^+$ promoted Feammox activity and stimulated the growth of Feammox-associated bacteria. This stimulation was accompanied by enhanced transformation of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) in both batch and column systems. Gene-level analyses further revealed substantial presence and activity of dehalogenation and fluoride-transport markers. The findings demonstrate the potential for leveraging Feammox processes as a bioremediation strategy for PFAS-contaminated environments, particularly in geochemical settings that support Feammox metabolism.

**Acknowledgments**

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# N-enriched biochar-iron cobalt mineral system for biomimetic reductive dehalogenation

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**ABSTRACT**

Bioreductive dehalogenation by organohalide-respiring bacteria is often limited by electron transfer efficiency and cofactor stability. We constructed a biomimetic system comprising bone char (N-enriched biochar), green rust (GR, Fe(II)-Fe(III) hydroxide), and cobalt hydroxide ($Co(OH)_2$) that outperforms microbial dehalogenation. GR serves as an Fe-S cluster mimic providing superior electron supply, while $Co(OH)_2$ forms Co-N active centers with biochar's nitrogen defects, analogous to vitamin $B_{12}$ cofactors. The layered morphology of GR and $Co(OH)_2$ enables self-assembly into heterojunctions, optimizing interfacial electron transfer. This Co-N center exhibits enhanced electron transfer compared to $B_{12}$, as confirmed by electrochemical analysis. The system not only dechlorinates trichloroethylene to acetylene but further hydrogenates it to ethylene/ethane. Quenching experiments and electrochemical tests reveal that reactive hydrogen species are not the dominant hydrogenation pathway. Instead, an electron-proton coupled transfer (EPCT) process drives both reductive dechlorination and subsequent hydrogenation. This biomimetic approach offers a robust platform for treating halogenated persistent organic pollutants.

# Demonstration Verification of Characterization Technology for DNAPLs in Typical Chemical Sites

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## ABSTRACT

Dense non-aqueous phase liquids (DNAPLs), which are composed of toxic organic contaminants like chlorinated solvents, are pervasive in soil and groundwater at industrial sites worldwide. To design efficient remediation strategies, precise characterization of DNAPLs is required. Since the traditional survey methods, such as invasive borehole-based investigations suffer from limited spatial coverage, a combined approach using non-intrusive geophysical methods alongside invasive techniques has been applied to image the DNAPLs distribution. However, this integrated strategy for DNAPLs imaging is limited since there is no unified technical specification for fine characterization. Moreover, the inaccurate fusion of multi-source data introduced by invasive and non-invasive approaches cannot preserve physically realistic patterns. To address these challenges, this study demonstrates and validates a characterization technology for DNAPLs at a typical chemical site, exploring a precision investigation method for DNAPL-contaminated sites based on multi-source data fusion. In this paper, the Electrical resistivity tomography (ERT) technique is combined with Membrane interface probe (MIP) to provide reliable DNAPLs characterization in a contaminated legacy chemical site in Jiangyin. Specifically, the ERT data is used to generate conductivity tomograms that delineate the abnormal area. The MIP data provides tomograms of pollutant concentration and soil lithology. The geophysical and MIP tomograms are then integrated with borehole measurements in a deep learning-based joint inversion framework to accurately characterize the highly irregular source zone architecture and provide a refined DNAPL image. Results demonstrate the standalone conventional sampling, geophysical methods, or hydrogeochemical surveys method fail to infer the DNAPLs in typical chemical sites. In contrast, the combined geophysical methods and hydrogeochemical surveys provide the necessary information to reconstruct the large-scale features of conductivity and concentration fields, while integrating geophysical data with sparse but accurate borehole data results in a high-resolution characterization of the source zone architecture.

# Microbially mediated organohalide cycling in soil

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ABSTRACT

Microbially mediated organohalide cycling in soil have profound implications for global element cycles and climate, but the phylogeny, coding potential and distribution of the halogenation-dehalogenation cycling microorganisms remain unknown. To explore the global-scale microbially-mediated halogenation and dehalogenation cycling of organohalides in soil, we first developed an organohalide-cycling gene database (HaloCycDB) to support organohalide-cycling metagenomics analyses; then, we collected 3000 metagenomes to reveal geographic distribution of organohalide-cycling microorganisms and functional genes at the global scale; the microorganisms and genes for halogenation and dehalogenation cycling of organohalides were further catalogued to explore novel taxonomic and genetic resources; last, the 'microorganism-enzyme-organohalide' patterns for reductive dehalogenation were analyzed and confirmed with protein structure prediction, molecular docking and laboratory cultivation experiments. To the best ofour knowledge, this study provides the first insight into the halogenation and dehalogenation cycling of organohalides in soil at the global scale, which provides a roadmap for exploring global organohalide-associated bioresources.

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# Organic Carbon Availability for Sulfate-Reducing Bacteria Governs the Dechlorination Reactivity of Biogenic Sulfidated Nanoscale Zero-Valent Iron

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## ABSTRACT

Sulfidated nanoscale zero-valent iron (S-nZVI) has been extensively studied for remediating soil and groundwater contaminated with chlorinated solvents. Among various sulfidation methods, biogenic sulfidation mediated by sulfate-reducing bacteria (SRB) has attracted attention due to its cost-effectiveness and sustainability. However, most existing studies assume idealized conditions with high-organic-carbon availability for SRB, which do not accurately represent the low-organic-carbon environments typically encountered in subsurface aquifers. In this study, *Desulfovibrio ferrophilus* IS5 was employed as a model SRB to biogenically sulfidate nZVI under varying levels of organic carbon. Our findings demonstrate that organic carbon availability critically influences both sulfidation pathways and dechlorination reactivity of biogenic sulfidated nZVI (Bio-S-nZVI). *D. ferrophilus*-mediated sulfidation significantly increased the abundance of $S^{2-}$ and $S_n^{2-}$ species, facilitated the replacement of iron oxides by iron sulfides, and enhanced $Fe^0$ exposure on the surface of iron nanoparticles. Although organic carbon limitation suppressed the apparent sulfate-reducing activity of *D. ferrophilus*, it did not substantially alter the elemental composition and speciation characteristics of the resulting Bio-S-nZVI particles. Under low-organic-carbon conditions, hydrogen generated from nZVI corrosion served as an alternative electron donor for *D. ferrophilus*, promoting the expression of its hydrogen metabolism gene (*hdyA*) and sulfate reduction gene (*dsrB*). Furthermore, in response to organic carbon limitation, *D. ferrophilus* appeared to adapt metabolically by enhancing electron transfer at the surface of Bio-S-nZVI particles. This facilitated electron extraction from internal $Fe^0$, intensified $Fe^0$ corrosion, and enhanced the particles' dechlorination reactivity toward chlorinated solvents. However, this process also promoted hydrogen evolution between Bio-S-nZVI and water, thereby reducing the electron efficiency for dechlorination relative to that of Bio-S-nZVI formed under high-organic-carbon conditions. This study provides new insights into tailoring biogenic sulfidation strategies of nZVI to enhance chlorinated solvents remediation under low-organic-carbon conditions.

**Acknowledgments**

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# Community Diversity Determines Colonization and Performance of Organohalide-respiring Bacteria

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**ABSTRACT**

Halogenated organic pollutants (e.g., chlorinated ethenes) are prevalent in the environment, causing severe harms to ecosystem function and public health. After decades of investigation, organohalide-respiring bacteria (OHRB) have been well recognized as the key microorganisms capable of degrading and detoxifying these toxic pollutants. Although bioremediation employing OHRB has been applied in the field, unsuccessful bioremediation cases are not uncommon due to failed colonization of the augmented OHRB (e.g., *Dehalococcoides*). Most prior studies focused on investigating the roles of abiotic factors (e.g., redox potential, pH) in affecting OHRB colonization, but it remains unknown how biotic properties of bioinoculants change colonization and performance of dechlorinating communities.

Here we manipulated the diversity and biomass of both bioinoculants to unveil the roles of community diversity in OHRB colonization. We found a notable influence of bioinoculant biodiversity on OHRB colonization and activity. Namely, bioinoculants with a moderate diversity exhibited the highest trichloroethene dechlorination rate, least accumulation of toxic intermediates (vinyl chloride), and the fastest OHRB growth. Moreover, higher augmentation biomass of bioinoculant resulted in more robust colonization of OHRB, accompanying with faster pollutant detoxification. Our findings demonstrate the important roles of bioinoculant diversity in affecting bioremediation performance.

# Hotspots for Microbial Dehalogenation of Persistent Organohalide Pollutants

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**ABSTRACT**

Persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) pose serious ecological and public health risks due to their persistence, toxicity, and bioaccumulation. Landfills, once viewed as passive sinks for municipal, industrial, and agricultural waste, are now recognized as complex biogeochemical hotspots hosting diverse microbiomes, yet their role in transforming halogenated contaminants remains poorly resolved. In tropical landfill sediments, POPs commonly occur at microgram-per-kilogram levels. To assess their biotransformation potential, long-term sediment microcosms were established and amended with representative contaminants, including Aroclor 1260, Penta-BDEs, and Deca-BDE. The landfill microbiomes achieved complete debromination of both Penta- and Deca-BDEs, generating over 30 previously unreported congeners and revealing diverse, novel transformation pathways. PCBs also underwent extensive dechlorination, underscoring the broad metabolic versatility of landfill-associated consortia. Quantitative molecular analyses showed that dehalogenation activity scaled with pollutant concentrations and was mediated by organohalide-respiring bacteria (e.g., Dehalogenimonas, Dehalobacter, and uncultivated Dehalococcoidia) harbouring known reductive dehalogenase genes. The consistently high abundance of sulfate-reducing bacteria suggests a key syntrophic role in supplying reducing equivalents that enable complete debromination and sustain long-term dehalogenation. Collectively, these findings position tropical landfills as natural hotspots for microbial detoxification of halogenated pollutants and highlight the ecological importance and nature-based remediation potential of landfill microbiomes for legacy and emerging contaminants.

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# Interactions of Zero-Valent Iron with Groundwater Environmental Components and Their Effects on Dechlorination

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## ABSTRACT

Zero-valent iron (ZVI) has been widely used in the remediation of groundwater contaminated by hydrocarbons in the past few decades. However, the influence of environmental components in groundwater, such as soil particles, sulfides (S(II)), and microorganisms, on the geochemical evolution and dechlorination performance of ZVI has not yet been systematically studied. Our research investigates the interactions between ZVI and groundwater components, specifically focusing on the following three aspects:

(1) **Interactions between ZVI and typical soil minerals**. We found that metal oxides and clay minerals primarily promote the corrosion of ZVI by water through adsorbing corrosion-resultant $Fe^{2+}$, rather than directly consuming $Fe^0$, while the quinone groups in humic acid as a typical of soil organic matter can directly consume $Fe^0$. These interactions enhance the reactivity of ZVI toward carbon tetrachloride in the short term, but shorten the service life of ZVI.

(2) **Interactions between ZVI and sulfide.** The sulfidation of ZVI by S(II) involves both indirect and direct sulfidation pathways, and ferrous ions can enhance the sulfidation efficiency. Biological sulfidation mediated by sulfate-reducing bacteria (SRB) affects the speciation of sulfur minerals on ZVI particle surface. Sulfidation can significantly enhance the reactivity and electron efficiency of ZVI towards trichloroethylene.

(3) **Interaction between ZVI and microorganisms.** We found that vitamin $B_{12}$, which could be secreted by environmental microorganisms, can broaden the reduction boundary of ZVI, enabling ZVI to efficiently reduce 1,2-dichloroethane. In addition, sulfidation can reduce the biotoxicity of nanoscale ZVI, thereby enhancing the synergistic dehalogenation of ZVI and dechlorinating microorganisms.

These findings are expected to offer important theoretical guideline for application of ZVI in practical remediation engineering.

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# Anaerobic degradation of chloromethane by ”Candidatus Chloromethanibacter formatiformans“ strain JHJ

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**ABSTRACT**

Chloromethane (CM) is the most abundant naturally-occurring halocarbon compound on Earth, with an estimated annual global emission of approximately 4,000 Gg and an atmospheric mixing ratio of about 600 ppt. Terrestrial vegetation, soils, biomass burning, and both biotic and abiotic processes in marine environments constitute the major natural sources of CM. CM acts not only as a greenhouse gas, with a 100-year global warming potential approximately 14 times that of $CO_2$, but also as an ozone-depleting substance, contributing an estimated 12–20% to stratospheric ozone loss. Moreover, CM poses significant risks to human health, as long-term or repeated exposure can impair reproductive capacity as well as the nervous system and liver and kidney functions. Therefore, elucidating the degradation and transformation pathways of CM is of great importance for understanding global climate change and ensuring ecological and environmental safety. Despite its significance, current knowledge of the biogeochemical cycling of CM, particularly its transformation behavior and driving factors in anaerobic ecosystems, remains extremely limited. This knowledge gap hampers our understanding of CM source–sink dynamics, key controlling factors, and its role in carbon cycling in soils and aquatic environments. In this study, anaerobic enrichment cultures were established using marine sediments as the inoculum and CM as the sole energy substrate, leading to the development of an anaerobic microbial consortium capable of completely degrading CM. By integrating high-throughput sequencing, anaerobic cultivation, isotope labeling, and multi-omics approaches, the core CM-degrading microorganisms within the enrichment culture were isolated and identified. Furthermore, the degradation pathways and transformation products of CM under anaerobic conditions were elucidated, and the associated metabolic pathways, key genes, and molecular regulatory mechanisms were characterized. These findings advance our understanding of the environmental fate of CM and the underlying microbial transformation mechanisms, providing a theoretical basis for more accurate assessments of the impacts of CM on global climate change.

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# Concerted microbial synergy and syntrophy facilitates anaerobic mineralization of 2,4-dichlorophenoxyacetic acid

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## ABSTRACT

The widespread use of 2,4-dichlorophenoxyacetic acid (2,4-D), a common herbicide, has led to its ubiquitous presence in subsurface environments, where anoxic conditions prevail. However, the mechanisms and pathways driving the complete breakdown of 2,4-D remain poorly understood. In this study, we investigated the microbial processes involved in the anaerobic degradation of 2,4-D. We demonstrated that 2,4-D is transformed through a stepwise process: initial ether bond cleavage to form 2,4-dichlorophenol, followed by reductive dechlorination to 4-chlorophenol and phenol, and eventual degraded to $CH_4$ and $CO_2$, as confirmed by $^{13}C$ isotope tracing. Key microbial population in this process is a novel *Dehalobacter* sp. strain, whose growth is coupled with the dechlorination of 4-chlorophenol to phenol, a metabolic bottleneck. Metagenomic analyses further revealed a syntrophic phenol-oxidizing community that enables the complete mineralization of 2,4-D. These findings provide new insights into the degradation and environmental fate of phenoxy herbicides.

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# Enhancing Electrochemical Reductive Defluorination of PFASs Using ZIF-67 Modified Cathode: Mechanistic Insights and Performance Optimization

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## ABSTRACT

**Introduction**
Per- and polyfluoroalkyl substances (PFASs) are persistent organic pollutants in which hydrogen atoms in the carbon chain are wholly or partially replaced by fluorine atoms. Due to their surface activity, hydrophobicity, acid and alkali resistance, thermal stability, and antioxidant properties, PFASs have been widely applied in various fields. With the gradual elimination of long-chained PFASs, the introduction of some short-chained substitutes in the environment can be expected to increase, a trend that is already observed. Compared to long-chained PFASs, these short-chained PFASs exhibit better solubility and are more difficult to degrade, making them more likely to penetrate natural and anthropogenic barriers and ultimately reach drinking water sources. 2-(Trifluoromethyl)-acrylic acid (TFMAA), as a fluorinated raw material/intermediate, has been proven to undergo biotransformation in natural environments
Electrochemical technology has gained increasing attention among degradation and removal of various micropollutants from water including recently also for PFASs degradation. Compared to oxidation, electrochemical reduction is more effective for PFASs degradation due to the strong electronegativity of fluorine atoms. However, the degradation efficiency of anionic PFASs using a cathode is often limited by the electrostatic repulsion between the cathode and PFASs molecules. Therefore, finding a material capable of simultaneously adsorbing PFASs molecules and catalyzing the generation of free radicals is likely to further improve the defluorination performance in the electrochemical reduction system.
Metal-organic frameworks (MOFs) have emerged as a research hotspot in recent years for PFASs adsorption in groundwater due to their developed pore structure, huge specific surface area, and the ease of adjusting surface chemical properties. A study has compared the adsorption effects of three MOFs (NU-1000, UiO-66, and ZIF-8) with different metal node compositions, nature of organic linker, pore sizes, and pore topologies on short-chained PFASs in groundwater. The results indicate that NU-1000 exhibits the best adsorption performance, UiO-66 demonstrates a relatively good adsorption effect on non-ionic PFASs, while ZIF-8 performs poorly in adsorbing short-chained PFASs. Recent studies have increasingly highlighted cobalt's potential to catalyze dehalogenation. Cobalt demonstrates a strong affinity with halogen atoms, as evidenced in cobalamin, the core of microbial reductive dehalogenation. Moreover, cobalt-containing chemical bonds, such as Co−P and Co−N bonds, can catalyze the production of H*. from water molecules or hydrogen ions, thereby promoting indirect reductive dehalogenation. Therefore, the electrochemical reduction system modified with ZIF-67, which contains Co−N structures, is likely to enrich PFASs on the electrode surface and catalyze PFASs reduction and defluorination by promoting the production of H*. However, the catalytic defluorination of short-chained PFASs using MOF-modified cathode has not yet been investigated, and the catalytic reduction mechanism remains unclear. In this study, a cobalt-containing MOF material, ZIF-67, was selected to modify the cathode and construct an electrochemical reduction system. Subsequently, ZIF-67 was carbonized to investigate its degradation performance and defluorination mechanism on the branched unsaturated PFAS, 2-(trifluoromethyl) acrylic acid.
**1.1 Characterizations**
Figure 1a-b display the SEM images of the cathode before and after modification. As shown in Figure 1a, the surface of the fiber, which is the skeleton of the carbon paper, is smooth in the bare carbon paper. After modification, crystals with regular dodecahedral structures are uniformly distributed on the surface of the carbon fiber (Figure 1b). Energy-dispersive X-ray spectroscopy (EDS) elemental mapping confirmed that C, N, and Co are evenly distributed over the surface of the fiber after modification (Figure 1c). XRD patterns of ZIF-67, carbon black, CP, and ZIF-67/C@CP are shown in Figure 1d. The 26.1° diffraction peak of carbon black and the 26.4° diffraction peak of blank carbon paper and modified carbon paper correspond to the graphitized crystal form of carbon. The diffraction peaks of ZIF-67/C@CP at 7.3°, 10.4°, and 12.7° correspond to the (011), (002), and (112) crystal planes, respectively, indicating the existence of ordered microporous structures. Additionally, ZIF-67/C@CP exhibited the main strong characteristic peak of ZIF-67 at 18.0° (Figure 1d), demonstrating the successful loading of ZIF-67.

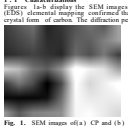


**Fig. 1.** SEM images of(a) CP and (b) ZIF-67/C@CP; (c) Elemental mapping ofZIF-67/C@CP. (d) XRD characterization ofZIF-67, carbon black, CP and ZIF-67/C@CP.
The composition and chemical states of the cathode surface after ZIF-67/C modification are shown in Figure 2. The XPS full spectrum illustrates the existence of N, $F^{2+}$and Co after ZIF-67/C modification (Figure 2a). The high-resolution N 1s spectra display characteristic peaks at 400.12 and 398.52 eV (Figure 2b), corresponding to pyrrolic N and pyridinic N. Additionally, the spin-orbit coupling of Co leads to the double peak Co $2p_{1/2}$ and Co $2p_{3/2}$, with characteristic peaks at 781.55 eV and 797.36 eV, 783.61 eV, 789.14 eV, and 802.68 eV corresponding to Co⁰, Co−N, and the satellite peak (Figure 2c). Regarding the high-resolution O 1s spectra in Figure 2d, the characteristic peaks at 533.43 eV and 534.30 eV correspond to the oxygen adsorbed on the surface of carbon paper and water molecules/hydroxyl radicals adsorbed on the surface of carbon paper, respectively. The above analysis further confirms the successful loading of ZIF-67 and carbon black on carbon paper.



**Fig. 2.** XPS characterization for (a) XPS spectra (b) N 1s (c) Co 2p and (d) O 1s ofZIF-67/C@CP.
**1.2 Adsorption and degradation ofTFMAA on ZIF-67 modified cathodes**
As shown in Figure 3a, the removal ratios of bare carbon paper (CP), carbon black-modified carbon paper (C@CP), ZIF-67-modified carbon paper (ZIF-67@CP), and ZIF-67/carbon black-modified carbon paper (ZIF-67/C@CP) after 48 hours were 6%, 8.97%, 4.63%, and 10.46%, respectively. The results show that ZIF-67 modification significantly improves the adsorption effect of the electrode on pollutants.
The degradation of TFMAA on CP, C@CP, ZIF-67@CP and ZIF-67/C@CP were studied at −1.2 V vs. Ag/AgCl. The removal efficiencies were 18.98% on CP, 92.31% on C@CP, 99.97% on ZIF-67@CP and 99.66% on ZIF-67/C@CP within 48 h (Figure 3b). The rate constant for ZIF-67/C@CP was 0.2356 $h^{-1}$, which is 1.24, 4.76 and 58.90 times higher than that for ZIF-67@CP (0.1896 $h^{-1}$), C@CP (0.0495 $h^{-1}$) and CP (0.0040 $h^{-1}$), as shown in Figure 3c. These results indicate that the addition of carbon black is indeed beneficial for ZIF-67 to further catalyze the degradation of TFMAA.
As shown in Figure 3d, the defluorination percentage of ZIF-67/C@CP, ZIF-67@CP, C@CP, and CP cathodes were 97.16%, 86.42%, 26.55%, and 9.43%, respectively. The ZIF-67 modified electrodes show a better defluorination performance than the other two electrodes, indicating that ZIF-67 has the potential to catalyze reductive defluorination. ZIF-67 coupled with carbon black shows the best degradation performance of the pollutant; this phenomenon may be due to the high conductivity and surface area of carbon black which is beneficial for providing more active sites



**Fig. 3.** Adsorption effect, degradation effect ofCP, C@CP, ZIF-67@CP, ZIF-67/C@CP. (a) Adsorption effect; (b) Removal effect (the error bars represent thestandard deviation ofduplicates); (c) Pseudo-first-order kinetic model; (d) Defluorination effect
**1.3 Electrochemical characterization**
Figure 4a-d presents the electrochemical characterization of different modified cathodes. The cyclic voltammetry curve shows that C@CP exhibits a better current response than the CP cathode due to the conductivity of carbon black (Figure 4a). Electrochemical impedance spectroscopy (EIS) can reflect the magnitude of interfacial transfer resistance near the surface of the electrode. As shown in Figure 4b, the smallest arc radius for ZIF-67/C@CP in EIS demonstrates the fastest interfacial transfer rate on the surface of ZIF-67/C@CP compared with other cathodes. The doping of carbon black in this study further enhances the catalytic effect of the modified cathode by increasing the specific surface area, improving the adsorption performance of the cathode surface, and enhancing the stability of ZIF-67 material.
The ZIF-67/C@CP cathode exhibits the strongest current density ($-2.29 \times 10^{-2}$ mA·$cm^{-2}$) at −1.2 V vs. Ag/AgCl, which is 3.09 times higher than that of the bare carbon paper cathode, demonstrating that the ZIF-67/C@CP cathode possesses a higher H* generation rate. This may be beneficial for the reduction and degradation of the pollutants (Figure 4c). Furthermore, we calculated the electrochemical double-layer capacitance (Cdl) of different electrodes (Figure 4d). C@CP shows the largest Cdl compared to the others, which is attributed to the large specific surface area of carbon black. ZIF-67@CP possessing a Cdl similar to CP, indicates that there may be a reunion in ZIF-67, which reduces the electrochemically active surface area. Due to the doping of carbon black, ZIF-67/C@CP shows a larger electrochemically active surface area than CP and ZIF-67@CP, which is beneficial for the degradation of TFMAA.

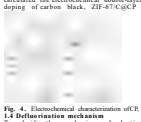


**Fig. 4.** Electrochemical characterization ofCP, C@CP, ZIF-67@CP, ZIF-67/C@CP (a) Cyclic voltammetry curve; (b) Electrochemical impedance spectroscopy; (c) Linear sweep voltammetry curve; (d) Corresponding double-layer capacitance (Cdl).
**1.4 Defluorination mechanism**
To clarify the mechanism of reductive defluorination catalyzed by the ZIF-67/C@CP cathode, different concentrations of TBA to quench radical were used in this work. Figure 5a shows that with the concentration of TBA increased from 0 to 10 mM, the pollution removal rate decreased from 99.66% to 88.17%. To analyze what free radicals play a catalytic role, we used 100 mM DMPO as the radical scavenger and employed EPR technology to detect the radical after applying voltage for 20 min. As shown in Figure 5b, nine characteristic peaks of DMPO-H were observed at ZIF-67/C@CP and ZIF-67/C@CP, while C@CP and CP cathodes did not exhibit characteristic peaks of DMPO-H. These results, in conjunction with the previous degradation capability (Figure 3b, 3d), indicate that H* catalyzed by ZIF-67 can promote the degradation of pollutants and improve the reductive defluorination performance upon TFMAA. Due to the fact that hydrated electrons are only generated under ultraviolet irradiation, and the interference of oxygen is excluded in this study, oxygen-containing free radicals will not be generated. Therefore, the only radical responsible for catalyzing defluorination through indirect electron transfer in this study is H*. The weak H* signal in the cathodyte may be due to the adsorption of most of the H* on the cathode surface.

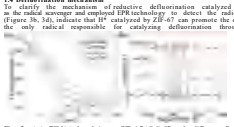


**Fig. 5.** (a) TFMAA degradation on ZIF-67/C@CP under different t-BuOH concentrations (the error bars represent thestandard deviation ofduplicates); (b) DMPO spin trapping ESR spectra ofCP, C@CP, ZIF-67@CP and ZIF-67/C@CP.
**1.5 Potential Degradation Pathways of TFMAA.**
To further elucidate the reductive defluorination pathway of TFMAA, high-performance liquid chromatography coupled with quadrupole time-of-flight mass spectrometry (HPLC-QTOF-MS/MS) was employed to analyze the intermediate products of TFMAA degradation. Figure S7 illustrates the changes in peak area of the detected degradation intermediates over 24 h, represented by TP 141.01, TP 91.00, TP 157.00, and TP 122. Initially, the C-C bond in the TFMAA molecule is hydrogenated and reduced to form a saturated branched structure. Some TFMAA molecules undergo direct C-F bond cleavage, followed by H-F exchange, resulting in the removal of one fluorine atom. Subsequently, the hydrogenated saturated structure, TP 141, undergoes a H-F elimination reaction, releasing one fluorine, while generating a C=C bond to form the TP 121.00 structure. TP 137.00 is hypothesized to be a product of an addition reaction occurring on TP 122. The intermediate product with one fluorine removed undergoes carbon chain shortening and continues defluorination to form TP 91.02, which contains only one C-F bond. The generated intermediate products continue to undergo reductive reactions with constant supply of electrons at the cathode, further removing fluorine atoms and ultimately achieving complete defluorination of the parent contaminant.

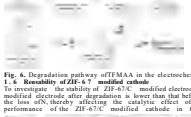


**Fig. 6.** Degradation pathway ofTFMAA in the electrochemical reductive system
**1.6 Reusability of ZIF-67 modified cathode**
To investigate the stability of ZIF-67/C modified electrodes, this section compared the changes in the element content of ZIF-67/C modified electrodes before and after degradation. Additionally, cyclic experiments were conducted to explore the recyclability and catalytic stability of ZIF-67 modified electrodes. As shown in Figure 7a, the percentage of C, N, and Co elements in the modified electrode after degradation is lower than that before degradation. It can be observed that the content of the Co element does not change significantly, while the content of the N element decreases significantly, indicating partial detachment of Co−N structures. This suggests that the saturated structure of Co−N4 may transform into an unsaturated structure due to the loss of N, thereby affecting the catalytic effect of ZIF-67. The reaction time was reduced to 24 hours, and the modified cathode was recycled and used four times at a voltage of −1.2 V. The results showed that the degradation rate of the same electrode material on TFMAA gradually increased with the increase of usage cycle (Figure 7b). It can be inferred that the improved performance of the ZIF-67/C modified cathode in the catalytic degradation of TFMAA in cycle experiments may be caused by the transition of Co−N bonds from the saturated to unsaturated state during the degradation process.

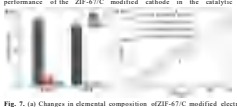


**Fig. 7.** (a) Changes in elemental composition ofZIF-67/C modified electrodes before and after degradation at −1.2 V; (b) Degradation rate ofTFMAA after four cycles.
**1.7 Degradation ofTFMAA on cathodes modified with ZIF-67 derived materials**
The Co−N2 structure formed by nitrogen loss caused by high temperature, exhibits better catalytic effects compared to the Co−N4 structure. Due to the loss of N in the ZIF-67 structure caused by 500-600 °C, this study chose a carbonization temperature of 550°C to optimize the catalytic performance of ZIF-67. In addition, when the temperature exceeds 750°C, a graphene layer will form on the surface of Co nanoparticles as a new active site, which also has catalytic activity. As a result, ZIF-67 materials carbonized at 550°C and 900 °C were prepared and loaded onto cathodes for reductive defluorination in this section. Figure 8 shows the catalytic effect of 550 °C-ZIF-67@CP and 900 °C-ZIF-67@CP on TFMAA reductive defluorination under −1.2 V. The 550 °C-ZIF-67@CP achieved a TFMAA removal rate of 98.33% and a defluorination rate of 97.99% within 24 h. The 900 °C-ZIF-67@CP slightly reduced the degradation performance upon TFMAA, with removal and defluorination rates of 88.65% and 78.73%, respectively. Observing the degradation rate and defluorination rate after 12 h of reaction, it can be seen that the carbonization of ZIF-67 at 550 °C has a better effect, and within 12 h, the degradation rate and defluorination rate have increased by 52.0% and 56.9%, respectively. This indicates that compared with high-temperature pyrolysis of ZIF-67 materials, low-temperature carbonization is more conducive to improving the catalytic activity of ZIF-67. From this result, it can be preliminarily inferred that the nitrogen loss caused by low-temperature carbonization is beneficial for improving the catalytic defluorination ability of ZIF-67, while the formation of cobalt nanoparticles surrounded by graphene by high-temperature carbonization does not significantly improve the catalytic effect of ZIF-67. Carbonization of ZIF-67 at 900°C did not further improve the catalytic performance of ZIF-67, which may be due to further nitrogen loss and thicker graphite layer wrapping, leading to a decrease in active sites.



**Fig.8.** Degradation effect of 550 °C-ZIF-67@CP and 900 °C-ZIF-67@CP compare to ZIF-67/C@CP. (a) Removal effect; (b) Defluorination percentage (the error bars represent thestandard deviation ofduplicates).
To further analyze the changes in elemental composition of carbon paper modified with ZIF-67-based materials, XPS characterization was performed on 550 °C-ZIF-67@CP and 900 °C-ZIF-67@CP. The peaks at 398.34 eV, 400.12 eV, and 402.77 eV correspond to pyridine nitrogen, pyrrole nitrogen, and graphite nitrogen, respectively (Figure 9a). During the carbonization process, the microstructure of the material underwent significant changes, and new graphite nitrogen peaks were observed. Compared with Figure 2b, it can be observed that as the carbonization temperature increases, the peaks of pyridine nitrogen and pyrrole nitrogen gradually decrease, and pyridine nitrogen is almost not observed on 900 °C-ZIF-67@CP.

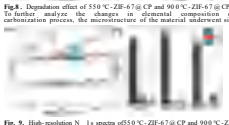


**Fig. 9.** High-resolution N 1s spectra of550 °C-ZIF-67@CP and 900 °C-ZIF-67@CP. (a) Removal effect (C/C0) (b) Changes in elemental composition after carbonization.
**1.8 DFT Calculation and Analysis**
To further analyze the catalytic mechanism of ZIF-67 and its carbonized material modified cathode, density functional theory (DFT) was employed in this section to calculate the catalytic production and adsorption capacity of different Co−N structures for H*. Figure 10 shows the calculated results of the free energies for H* generation and the energy for H* adsorption $E_{ads}$(H*) by the four constructed structures. As shown in Figure 10a, ΔGiH* of Co−N1, Co−N2, Co−N3, and Co−N4 are 0.02 eV, 0.02 eV, 0.06 eV, and 0.16 eV, respectively. Typically, research suggests that catalytic materials with ΔGiH* < 0.2 eV exhibit hydrogen evolution activity, indicating that all four structures can catalyze the production of H*. The DFT calculation results of Co−N structures connected to different numbers of N show that the lower the N content, the smaller the ΔGiH*. Among them, Co−N1 and Co−N2 structures exhibit the smallest ΔGiH*, indicating that a certain degree of N loss is conducive to improving the ability of cobalt nitrogen structures to produce H*, and Co−N1 and Co−N2 structures are most favorable to catalyzing the production of H*. Therefore, the significant improvement of the catalytic defluorination performance on the electrode 330 °C-ZIF-67@CP significantly was caused by the loss of N leading to an increase in the proportion of Co−N1 and Co−N2 structures in the ZIF-67 material.
Figure 10b shows the adsorption energies of four different structures for H*. The four Co−N structures with different cobalt nitrogen ratios have negative adsorption energies for H*, indicating that these structures can stably adsorb H*. Among them, the Co−N1 and Co−N2 structures have the lowest adsorption energies, suggesting that these two structures have the strongest ability to adsorb H*. The above calculation results indicate that all four Co−N structures are conducive to catalyzing the production of H* and stabilizing the adsorption of H* on the cathode surface. Among them, the Co−N1 and Co−N2 structures have the strongest ability to produce and adsorb H*. Furthermore, by analyzing this calculation result together with Figure 5b above, it can be confirmed that the low H* signal in the cathodyte is indeed a result of H* adsorption on the cathode surface.

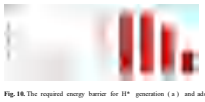


**Fig. 10.** The required energy barrier for H* generation (a) and adsorption energy diagram ofH* (b) on different Co−N structures.

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# Applying Compound Specific Stable Isotope Analysis for Characterizing the Biotransformation of Hexachlorocyclohexane Isomers by Different Methanogens

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**ABSTRACT**

The environmental persistence and toxicity of hexachlorocyclohexane (HCH) isomers continue to pose significant global remediation challenges. While the reductive dechlorination of HCH isomers by organohalide-respiring bacteria (OHRBs) has been extensively studied, forming the mechanistic basis for many bioremediation approaches, the potential for transformation by ubiquitous methanogenic archaea remains poorly characterized. This knowledge gap limits our ability to predict HCH fate in complex anoxic environments, such as contaminated aquifers and sediments, where methanogens are often abundant, especially after the depletion of preferred terminal electron acceptors. To address this, we applied compound-specific stable carbon isotope analysis (CSIA) to systematically quantify and characterize the biotransformation of α-, β-, γ-, and δ-HCH isomers by three distinct methanogens: *Methanobacterium* sp. strain KD21, *Methanosarcina mazei* WH, and *Methanospirillum hungatei*. Through high-resolution monitoring of isotopic composition ($\delta^{13}C$) in residual substrates, we derived precise carbon isotope enrichment factors ($\varepsilon_C$) for each organism-isomer pair. These $\varepsilon_C$ values, which serve as intrinsic fingerprints of the enzymatic reaction mechanism, revealed distinct patterns of substrate selectivity and transformation kinetics among the methanogens, suggesting pronounced differences in both transformation rates and apparent pathways among the methanogens, highlighting unique substrate specificities. Crucially, a systematic comparison of these novel $\varepsilon_C$ data with the well-established isotope fractionation patterns for HCH transformation by pure cultures of OHRBs (e.g., *Dehalococcoides* and *Dehalobacter*) uncovered statistically significant and fundamentally divergent isotopic fractionation patterns. For key isomers, the magnitude and even the direction of carbon isotope fractionation observed for methanogens contrasted sharply with those characteristic of reductive dehalogenases from bacteria like *Dehalococcoides*. This divergence strongly suggests that methanogens employ co-metabolic or alternative enzymatic mechanisms for HCH transformation that are isotopically distinguishable from the dedicated reductive dehalogenases used in organohalide respiration. The study yields a new, comprehensive set of enzymatic isotope effect (EIE) data for assessing HCH fate in anoxic environments.

The implications of this work are twofold. First, it fundamentally expands the conceptual model of anaerobic HCH degradation by quantitatively demonstrating that methanogenic archaea can contribute to contaminant transformation through pathways isotopically separable from OHRB activity. Second, it delivers a crucial new set of isotopic benchmarks ($\varepsilon_C$ values). These data significantly advance the application of CSIA as a powerful diagnostic tool in the field. By enabling the differentiation between OHRB-mediated dechlorination and methanogenic co-metabolism in situ, our results provide environmental scientists and remediation engineers with a refined capacity to attribute degradation activity, assess the contribution of diverse microbial guilds, and accurately evaluate the progression and endpoint of natural attenuation at complex HCH-contaminated sites. This mechanistic understanding is essential for developing next-generation bioremediation strategies that account for and potentially harness the full metabolic potential of anaerobic microbial communities.

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# Nitrate Reduction Influences the Structure and Function of Dehalogenating Community

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**ABSTRACT**

Nitrate and chlorinated solvents, such as tetrachloroethene (PCE) and trichloroethene (TCE), frequently co-exist as widespread contaminants in subsurface environments such as soil and groundwater, due to agricultural and industrial activities. This study investigated the impact of nitrate-associated biotransformation on microbial reductive dehalogenation which is the most dominant natural process for detoxifying chlorinated solvents. Anaerobic microcosms were established with river sediment, amended with PCE and varying nitrate concentrations (0, 0.5, 1, 5, 10 mM) to stimulate both reductive dehalogenation and denitrification process. In nitrate-free microcosms, 86.03 ± 2.99 μmol PCE was completely dehalogenated to stoichiometric amounts of non-toxic ethene within 35 days at a total rate of 98.32 ± 3.42 μM $Cl^-$ released per day. The dehalogenation process could be separated into two stages, PCE to *cis*-dichloroethene (*c*DCE) via TCE was the first stage, which was accomplished in less than 9 days with a rate of 252.89 ± 15.88μM $Cl^-$ released per day, and *c*DCE to ethene through vinyl chloride (VC) was the second stage, which took more than 20 days at a rate of 71.11 ± 9.99 μM $Cl^-$ released per day. In contrast, the presence of denitrification (nitrate reduction to $N_2$) strongly inhibited dehalogenation, leading to slower rates and incomplete dehalogenation, with *c*DCE as the major accumulation product. High-throughput sequencing of the 16S rRNA gene revealed that the sequential dehalogenation of PCE to non-toxic ethene were contributed by a consortium containing *Sulfurospirillum*, *Tirchlorobacter*, *Dehalobacter* and *Dehalococcoides*. Under nitrate-amended conditions, the community shifted markedly: *Sulfurospirillum* (capable of PCE-to-*c*DCE dehalogenation) became dominant, while *Dehalococcoides* was strongly suppressed. Then, we investigate the effects of nitrate and nitrite on dehalogenation driven by *Sulfurospirillum multivorans* strain DSM 12446 (capable of PCE-to-*c*DCE dehalogenation) and *Dehalococcoides mccartyi* strain BAV1 (capable of *c*DCE-to-ethene dehalogenation). We demonstrated that whereas nitrate (at concentration up to 10 mM) did not inhibit reductive dechlorination, its reduction product-nitrite, was an inhibitor at much lower concentrations (e.g., 5 μM for strain BAV1). We further investigated the effects of nitrite on two enzymes essential for electron transfers and carbon-halogen bonds cleavage in OHRB: hydrogenase ($H_2$ase) and reductive dehalogenase (RDase). Nitrite inhibited both enzymes, and enzyme kinetic analysis of $H_2$ase from strain BAV1 revealed that 50 μM nitrite reduced the $V_{max}$ from 8.32 to 6.58 μmol/min/mg, while the $K_m$ remained constant (~0.3 mM). This pattern identifies nitrite as an irreversible inhibitor of $H_2$ase. These findings provide a mechanistic understanding of how nitrate and nitrite inhibit reductive dehalogenation, offering important insights for optimizing bioremediation strategies at sites co-contaminated with chlorinated compounds.

**Keywords:** reductive dehalogenation, denitrification, microbial community, bioremediation

# Coupling Sulfidated Zero-Valent Iron with Organohalide Respiring Bacteria for Remediation of Mixed Chlorinated Hydrocarbons Contamination

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**ABSTRACT**

Chemical reduction by sulfidated nanoscale zero-valent iron (S-nZVI) and biodegradation by organohalide-respiring bacteria (OHRB) are two key technologies for remediating chlorinated hydrocarbons (CHCs) in soil and groundwater. In actual contaminated sites, however, CHCs often coexist as mixtures, making complete degradation difficult with a single treatment approach:neither S-nZVI cannot degrade certain chlorinated hydrocarbons such as 1,2-dichloroethane (1,2-DCA), nor the activity of OHRB is susceptible to electron donor limitation and inhibition by high contaminant concentrations. This study investigated the synergistic degradation mechanisms of S-nZVI and Dehalococcoides mccartyi strain 195 (Dhc 195) on a mixture of trichloroethene (TCE) and 1,2-DCA under simulated source zone (high-concentration) and plume zone (low-concentration) conditions. The introduction of quartz sand was used as a natural porous medium, aiming to imulate the porous media conditions of actual subsurface aquifers. A staged remediation strategy is proposed: microbial remediation can be applied in low-concentration zones, whereas in high-concentration zones, S-nZVI can first be introduced for chemical pretreatment. This step addresses the lag phase often associated with biological reductive dechlorination and reduces pollutant concentrations to levels that do not inhibit microbial activity. Subsequent bioaugmentation with Dhc 195 enables effective and complete removal of CHCs. Under low contamination levels, direct addition of S-nZVI inhibited the dechlorination activity of Dhc 195, leading to reduced TCE degradation rates and accumulation of intermediates. In high-concentration conditions, due to the inhibitory effect on microbial activity the abiotic pathway dominated by S-nZVI converted TCE to ethene, acetylene, and other products, but 1,2-DCA remained persistent. Notably, the introduction of quartz sand as a porous medium significantly alleviated the contact toxicity of S-nZVI toward Dhc 195, especially in low-concentration systems, the TCE degradation rate was nearly doubled compared to that of the microbial-only system, and the system maintained the ability to degrade 1,2-DCA and intermediates such as cis-DCE. These results indicate that porous media not only reduce the inhibitory effect of S-nZVI but also promote synergy between biological and abiotic processes. This study provides theoretical and technical support for the remediation of CHCs mixtures in actual soil and subsurface aquifers. By combining material injection strategies with the natural effects of porous media, a more efficient and stable bio-abiotic collaborative remediation system can be established.

**Acknowledgments**

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# From Antagonism to Synergy: Porous Media Regulate the Coupled Degradation of Trichloroethylene by Nanoscale Zero-Valent Iron and Reductive Dechlorinating Bacteria

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**ABSTRACT**

Trichloroethylene (TCE) is a typical recalcitrant mixed contaminant at industrial decommissioned sites. The coupled system of nano zero-valent iron (nZVI) and reductive dechlorinating bacteria theoretically possesses the potential for synergistic TCE degradation; however, antagonistic effects are often observed in laboratory liquid systems, contradicting the synergistic behavior demonstrated in actual field scenarios. This discrepancy may be related to the modulating role of porous media commonly present in actual aquifers. This study selected quartz sand and three typical clay minerals (Illite, Kaolinite, and Montmorillonite) to systematically investigate the regulatory mechanisms of porous media on the coupled degradation of TCE by nZVI and its sulfidated particles (S-nZVI) with *Dehalococcoides mccartyi* strain 195 (Dhc 195) under simulated groundwater conditions. The results revealed that porous media, especially clay minerals, are key environmental factors that shift the chemical-biological coupled remediation of TCE from a "potential antagonism" in the laboratory to an "actual synergy" in the field. In media-free systems, the coupling of nZVI and Dhc showed distinct antagonism, whereas the introduction of clay minerals significantly enhanced TCE degradation efficiency and even achieved complete dechlorination. Meanwhile, porous media notably modulated the hydrogen evolution behavior of nZVI: clay minerals promoted hydrogen evolution of nZVI but inhibited it from S-nZVI. In the coupled system, the concentration of dissolved hydrogen in the liquid phase was significantly reduced, indicating an improvement in the utilization of hydrogen by Dhc 195. It was confirmed that the addition of clay minerals optimized the electron transfer efficiency of iron to bacteria. On the other hand, owing to their high specific surface area and strong adsorption capacity, clay minerals could adsorb and sequester nanoparticles, mitigating direct contact between nZVI and bacteria and effectively alleviating the biological inhibition of Dhc 195 by nanomaterials. Moreover, the metabolic activity and extracellular polymeric substance (EPS) attachment of Dhc 195 drove the structural evolution of nanoparticles toward porosity and fragmentation, exposing more active sites ($Fe^0$). Combined with the effects of mineral loading and sulfidation modification, this process facilitated dynamic evolution of the nano- iron interfacial morphology. This study provides new insights for enhancing chemical-biological coupling in the in situ remediation of TCE and promoting stable, efficient field applications.

**Acknowledgments**

This study was financially supported by the NSFC (No. 42225704 and 42577267).

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Wang, B., Zhu, Y., Dong, W., Wang, C., Yang, L., Fan, Y., Sun, T., Shan, Y., Wu, Z. and He, F. Unveiling the Differential Impacts of S-nZVI and nZVI on Microbial Dechlorination of Trichloroethene by Dehalococcoides. Environ. Sci. Technol. 2025, 59(27), 14089-14102.

# Rare Chlorinated Pesticide-Degrading Microorganisms from Aral Sea Sediments

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**ABSTRACT**

The Aral Sea represents an extreme hypersaline lake with exceptionally high concentrations of dissolved salts. Over many decades, it has been exposed to intense anthropogenic pressure — primarily from chlorinated organic pesticides — leading to the formation of a unique microbial community adapted to harsh environmental conditions.

Soils and bottom sediments serve as major reservoirs of microbial diversity, harboring the largest number of prokaryotic cells on Earth (Flemming and Wuertz, 2019). It is widely acknowledged that a substantial proportion of bacteria remain uncultivable — a phenomenon described as the *great plate anomaly* as early as the beginning of the 20th century. Estimates of cultivability remain debated, ranging from 0.01 to 1% (Staley and Konopka, 1985). The prevailing view in the scientific community holds that the majority of bacterial taxa fail to grow on standard laboratory media due to unsuitable growth conditions, such as the absence of essential microelements, nutrients, or proper environmental parameters. A cultivation approach based on soil microaggregate enrichment has previously been demonstrated as an effective strategy for isolating rare bacterial species (Yin et al., unpublished).

In this study, we applied a similar approach to cultivate microaggregate fractions of the Aral Sea sediments on nutrient media to isolate rare microbial taxa capable of degrading DDT and lindane. Previously uncultured *Acidimicrobiia* bacteria possessing linE, linG, linH, and linJ genes were isolated, along with *Trichoderma* spp. strains grown on lindane-containing media. Moreover, previously uncultured halophilic archaea of the family *Haloferacaceae* were identified as capable of tolerating and growing at high concentrations of DDT and lindane in enrichment cultures.

Metagenomic analysis coupled with microbiological isolation revealed that both microbial diversity and total abundance were substantially higher in sediments than in the water column. Pesticide-degrading strains were isolated exclusively from the sediment samples and not from the overlying water of the Aral Sea.

**Acknowledgments**

The isolation and characterization of uncultured bacteria were carried out under the state assignment of Lomonosov Moscow State University. The analysis of pesticide residues was supported by the Russian Science Foundation, project No. 25-14-00073

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# A Field Study to Examine Applicability of a Novel Groundwater in-situ Bioremediation Method to Co-optimize Dechlorination of Chlorinated Ethenes and Subsurface Ecological Stability

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## ABSTRACT

Groundwater contamination by chlorinated ethenes, including tetrachloroethene (PCE) and trichloroethene (TCE), remains a persistent environmental challenge due to their widespread historical use and the limited effectiveness of conventional remediation techniques. In situ bioremediation has been increasingly applied as a cost-effective and environmentally sustainable alternative; however, existing remediation designs have primarily focused on maximizing contaminant removal, with limited consideration of subsurface ecological impacts induced by substrate addition or microbial bioaugmentation.

In a previous study, we developed a novel microcosm-based in situ bioremediation design framework that determines the injection concentrations of a primary substrate (lactate) and an exogenous microbial consortium (JL-1) to co-optimize reductive dechlorination performance and subsurface ecological stability. Because this framework was derived solely from laboratory microcosm experiments, its applicability under field conditions remained uncertain.

In this study, we evaluated the field applicability of the proposed design framework by comparing field observations with model simulations parameterized using microcosm-derived results at a PCE- and TCE-contaminated groundwater site in South Korea. Following the injection of lactate and the JL-1 consortium at concentrations determined by the optimization framework, chlorinated ethenes and their biodegradation products (DCE, VC, ethene, and chloride) were monitored alongside functional genes and target microbial populations using high-throughput qPCR. Subsurface ecological responses were assessed using ATP activity measurements and flow-cytometric analyses, including cell fingerprinting, live cell density, and microbial diversity.

Field-scale concentrations of PCE, TCE, and DCE were well reproduced by reactive transport model simulations, while a higher-than-predicted VC-to-ethene conversion was observed under field conditions. Ecological disturbance quantified by flow-cytometric fingerprinting distances showed strong consistency between laboratory and field observations, whereas ATP activity and other flow-cytometric indicators exhibited discrepancies. Overall, the results demonstrate the field applicability of the proposed in situ bioremediation design framework for co-optimizing contaminant removal and subsurface ecological stability, while highlighting the need for further investigation into enhanced VC-to-ethene conversion processes under field conditions.

**Acknowledgments**

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# Microbial Processes Impacting Fate and Transport of PFASs

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**ABSTRACT**

The use of aqueous film-forming foam (AFFF) containing perfluoroalkyl acids (PFAAs) and polyfluoroalkyl substances (aka precursors) as fire suppressants has led to widespread soil and groundwater contamination with per- and polyfluoroalkyl substances (PFASs). While PFAAs are highly resistant to biodegradation, many precursors can undergo biotransformation, as demonstrated in the laboratory and at contaminated sites. Little is known about the specific processes, microorganisms, and enzymes involved in precursor transformation and defluorination, limiting our ability to predict, and potentially manage (i.e., control), precursor fate and transport at PFAS-impacted sites.

The soil isolate *Pseudomonas* sp. strain 273 grows aerobically on terminally fluorinated alkanes, including decanes with poly- or perfluorinated carbons. Catabolic products include inorganic fluoride and poly-/ perfluorinated short-chain fatty acids. Strain 273 also desulfonates 4:2, 6:2, and 8:2 fluorotelomer sulfonates to acquire sulfur as a nutrient for growth, generating fluorotelomer carboxylic acids (FTCAs) as intermediates. Batch incubation experiments revealed that this bacterium transforms and defluorinates FTCAs containing even numbers of non-fluorinated carbon atoms (e.g., n:2 and n:4 FTCAs), but not FTCAs with odd numbers of non-fluorinated carbon atoms (e.g., n:3 or n:5 FTCAs). Transformation of n:2 FTCAs primarily yields inorganic fluoride, the corresponding [n-1]:3 FTCAs, perfluorocarboxylic acids (PFCAs) with one less perfluorinated carbon (i.e., [n-1] PFCAs), and trace amounts of shorter-chain (i.e., [n-2], [n-3]) PFCAs.

Although strain 273 does not defluorinate n:3 FTCAs, lipidomic analysis revealed the covalent incorporation of intact n:3 FTCAs (e.g., 5:3, 7:3, 8:3, and 9:3 FTCA) into fatty acid acyl tails of glycerophospholipids when strain 273 cultures were exposed to n:3 FTCAs during growth. Semi-quantitative lipidomic analysis estimated that a substantial fraction of the bacterium's phospholipid pool contains n:3 FTCA when grown under laboratory conditions. Notably, this incorporation process also occurs at environmentally relevant concentrations of n:3 FTCAs. Incorporation of n:3 FTCAs into the phospholipid pool was not limited to strain 273 and was observed in other axenic bacterial cultures. The process of covalent incorporation into phospholipids (i.e., the formation of bacterial fluoromembranes) represents an unrecognized sink for n:3 FTCAs. Considering that n:3 FTCAs are intermediates in the biotransformation of various precursor classes, bacterial incorporation of n:3 FTCAs can potentially impact precursor fate, longevity, bioaccumulation, and biomagnification. This research exemplifies how pure culture laboratory studies can unravel processes that likely impact PFAS fate and transport under *in situ* conditions.

**Acknowledgments**

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# Nitrous Oxide Modulates Reductive Dechlorination and other Biogeochemical Processes

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**ABSTRACT**

Nitrogen (N) cycling is fundamental to all microbiomes. Microbial, abiotic, and coupled biotic-abiotic processes turn over fixed N and produce nitrous oxide ($N_2O$) in both pristine and disturbed environments. The atmospheric $N_2O$ concentration (currently ~338 parts per billion) would give rise to aqueous phase (e.g., groundwater, soil moisture) $N_2O$ concentration in the low nanomolar range; however, orders of magnitude higher $N_2O$ concentrations exceeding 100 micromolar are observed in groundwaters. Similar observations have been made in soils, where $N_2O$ formation is highly dynamic over spatial and temporal scales, with rainfall, fertilization, and freeze-thaw demonstrated to cause hot spots and hot moments of exceptionally high soil $N_2O$.

$N_2O$ serves as a respiratory electron acceptor for bacteria possessing $N_2O$ reductase (NosZ), but otherwise has been considered biologically inert with no impact on microbial community dynamics and functions. Recent work, however, rejects this premise, highlighting that $N_2O$ is a potent inhibitor of corrinoid-dependent enzymatic reactions impacting methionine biosynthesis, methanogenesis, and organohalide respiration. Batch culture incubations demonstrated that acetoclastic methanogenesis, estimated to account for two-thirds of the annual 1 billion metric tons of biogenic methane ($CH_4$), was very sensitive to $N_2O$, with inhibitory constants ($K_I$ values) in the range of 18–25 micromolar, followed by hydrogenotrophic ($K_I$, 60–90 µM) and methylotrophic ($K_I$, 110–130 µM) methanogenesis. The analyses show that micromolar concentrations of $N_2O$ decrease or abolish $CH_4$ production, reduce methanogen growth yields, and exhibit progressively negative feedback on microbial $CH_4$ production. Organohalide respiration, a key process for the biogeochemical cycling of chlorine and bioremediation of environments impacted with anthropogenic chlorinated organic compounds, hinges on the activity of corrinoid-dependent reductive dehalogenases. Laboratory cultivation experiments demonstrated that $N_2O$ concentrations in the low micromolar range decreased dechlorination rates and resulted in incomplete dechlorination of tetrachloroethene (PCE) in *Geobacter lovleyi* and of *cis*-1,2-dichloroethene (cDCE) and vinyl chloride (VC) in *Dehalococcoides mccartyi* axenic cultures. $N_2O$ did not inhibit corrinoid-independent fumarate-to-succinate reduction in *Geobacter lovleyi*, supporting that $N_2O$ interferes with reductive dechlorination by reacting with super-reduced Co(I)-corrinoids of reductive dehalogenases. Kinetic analyses revealed a best fit to the noncompetitive Michaelis-Menten inhibition model and determined $N_2O$ inhibitory constants, $K_I$, for PCE and cDCE reductive dechlorination of 40.8 ± 3.8 and 21.2 ± 3.5 micromolar in *Geobacter lovleyi* and *Dehalococcoides mccartyi*, respectively. The lowest $K_I$ value of 9.6 ± 0.4 micromolar was determined for the VC to ethene reductive dechlorination step. Considering that soil and groundwater $N_2O$ concentrations often exceed the measured $K_I$ values, especially in watersheds impacted by nitrate runoff from agricultural sources, $N_2O$ is an underappreciated modulator of organohalide respiration and other corrinoid-dependent processes.

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# Comprehensive Assessment of Soil Heavy Metal Pollution in the Historic Center of Krakow, Poland: Geostatistical and Machine Learning Study

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**ABSTRACT**

Soil pollution with heavy metals represents one of the most serious environmental threats in urban areas, as these metals readily accumulate and can persist for hundreds or even thousands of years, posing risks to human health through the food chain. Urban soils, including those in Krakow, exhibit significantly elevated concentrations of heavy metals due to anthropogenic activities such as industrial emissions, traffic, and coal combustion. In Krakow, the highest levels of pollution are observed in the city center and industrial zones, underscoring the strong human impact, and continuous monitoring of heavy metal concentrations is crucial for public health protection. Investigating the distribution and sources of these metals also provides insights into the historical influence of human activity on the urban environment.

The novelty of this study lies in its comprehensive assessment of heavy metal pollution across the entire central area of Krakow, integrating multiple pollution indices with advanced geostatistical and machine learning approaches. The aim of the study is to evaluate topsoil contamination by heavy metals, explore their relationships with soil properties, and compare traditional and modern analytical methods to elucidate spatial patterns and environmental risks.

In this study, the concentrations of six heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) were measured in over 50 topsoil samples from the city center of Krakow, alongside key soil properties including texture, pH, $CaCO_3$, and total organic carbon. Heavy metal contamination was assessed using multiple pollution indices, such as $I_{geo}$, *CSI*, and *PLI* (Kowalska et al., 2018), while geostatistical and machine learning methods were employed to map spatial distribution and identify pollution hotspots. Elevated concentrations of Pb, Cd, and Cu were particularly observed near the Wisła River, the main railway station, and other high-traffic areas. A comparative meta-analysis contextualized these results within Europe, highlighting spatial and temporal trends in soil pollution across the continent.

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# Distribution and Environmental PReferences of Potential Mercury Methylators in Paddy Soils across China

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## ABSTRACT

Neurotoxic methylmercury (MeHg) accumulation in rice grain primarily originates from paddy soils, where inorganic mercury (Hg) is converted into MeHg by microorganisms harboring the *hgcAB* gene pair. Although paddy soils represent important reservoirs of Hg-methylating microorganisms, their large-scale biogeographic distribution, phylogenetic diversity, and metabolic potential remain insufficiently understood. Here, we integrated *hgcA* gene amplicon sequencing with deep metagenomic analyses to investigate Hg-methylating communities across major rice-producing regions of China, spanning approximately 3600 km in latitude and 1300 m in altitude.

Amplicon sequencing revealed pronounced spatial variation in Hg-methylating communities, with significantly higher *hgcA*$^+$ microbial community richness in tropical and subtropical paddy soils than in temperate regions. *Geobacteraceae*, *Smithellaceae*, and *Methanoregulaceae* were identified as dominant *hgcA*$^+$ families associated with MeHg production, collectively accounting for up to 77% of total *hgcA* sequences. Hierarchical partitioning analyses indicated that soil pH was the primary environmental factor shaping *hgcA* distribution in *Geobacteraceae* (14.8%) and *Methanoregulaceae* (16.3%), whereas altitude explained a substantial proportion of variation in *Smithellaceae* (21.4%), suggesting distinct environmental niche pReferences among major Hg-methylating lineages. Machine-learning-based spatial prediction further revealed heterogeneous distributions of dominant methylators across Chinese paddy ecosystems, enabling improved regional prediction of MeHg production potential.

Metagenomic sequencing of the representative paddy soils substantially expanded the known diversity of Hg-methylating microorganisms, identifying 6,057 *hgcA* genes spanning 27 microbial phyla. We reconstructed 152 high-quality metagenome-assembled genomes (MAGs) carrying conserved *hgcAB* domains, predominantly affiliated with Nitrospirota, Desulfobacterota, and Acidobacteriota. Importantly, several previously uncharacterized putative Hg-methylating lineages were recovered, including one candidate phylum and two candidate classes. Metabolic reconstruction revealed that putative Hg-methylators possess diverse functional capacities extending beyond Hg transformation, including nitrogen fixation, sulfate reduction, arsenic methylation, antibiotic resistance, and heavy-metal stress response pathways, indicating strong coupling between Hg methylation and broader biogeochemical processes.

Collectively, our results reveal extensive phylogenetic and metabolic diversity of Hg-methylating microorganisms and demonstrate that their distribution across paddy soils is governed by environmental filtering and ecological niche differentiation at large spatial scales. These findings provide new ecological and genomic insights into microbial determinants of MeHg production and establish a framework for improving prediction of MeHg accumulation risk in rice paddy ecosystems.

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# Trace Elements Accumulation Patterns in Cryoconites and Periglacial Soils of the Central Caucasus Mt (Russia) and Northern Tian Shan Mt (Kazakhstan)

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**ABSTRACT**

Dark-colored organomineral supraglacial sediments, known as cryoconites, constitute a primary source of elements on glacier surfaces, which are subsequently transferred to adjacent alpine soils via fluvioglacial mechanisms. Accumulation and translocation of trace elements may pose risks not only for ecosystems but also for local agriculture and water quality, especially in case of anthropogenic load nearby. Therefore, the aim of this research is to study features of trace elements accumulation in cryoconites and local alpine soils in two different areas, both with anthropogenic load and background. The first study area is represented by surroundings of the Elbrus Mt, Central Caucasus, where samples of cryoconites were taken from glaciers Skhelda, Garabashi and Maly Azau. Soils sampling included two Leptosols at the Baksan Gorge and Umbric Leptosol, Eutric Histosol and Leptic Umbrisol, according to WRB, at the Terskol Gorge. The second study area is located at the Ile Alatau Mt, Northern Tian Shan, where samples were taken from Morenny and Bogdanovicha. Sampled soils were defined as Lithic Leptosol and Skeletic Regosol at the Big Almaty Valley and Leptic Umbrisol at the Left Talgar Gorge. Content of Cu, Zn, Ni, Pb and Cd was defined by atomic absorption spectrometry according to ISO 11047, following Kruskal-Wallis ANOVA analysis and calculation of pollution indices. Results showed that cryoconites of the Skhelda and Maly Azau glaciers were the least polluted with all studied trace elements due to their remoteness from the touristic and mining sites with all pollution indices indicating absence of pollution. On the other hand, Garabashi and Bogdanovicha glaciers were the most polluted with almost all trace elements. The highest pollution was observed with Zn (max. 125 mg·kg$^{-1}$) due to both elevated natural background and local touristic activities. For the most of trace elements we observed significant difference in their content between anthropogenically loaded and background glaciers of 2 sites, indicating human role in pollution. Interestingly, background Morenny Glacier was in between and did not differ significantly from other glaciers, that is probably connected with long-distance transfer of industrial pollutants. Translocation of polluted cryoconites together with local human activities led to accumulation of trace elements in soils of Baksan and Left Talgar Gorges. Content of almost all of them was significantly higher in these gorges than in background Big Almaty Valley and Terskol Gorge, especially for Zn (max. 120 mg·kg$^{-1}$) and Ni (max. 40 mg·kg$^{-1}$). In general, cryoconites efficiently accumulated all trace elements, similarly to local soils and more. Ecological index PERI showed high risk load of sites with human activities, indicating necessity of alpine areas monitoring to preserve quality of local ecosystem services.

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# Mineral-organic matter association controls colloidal arsenic mobility from soil to lake

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## ABSTRACT

Arsenic (As) contamination from mine tailings is a global environmental concern, yet most studies have focused on acidic systems where Fe(hydr)oxides dominate and arsenate binding is relatively well understood. In contrast, neutral to carbonate-rich environments remain poorly studied, despite their global relevance. These settings, including carbonate-buffered tailings and karst soils, are often assumed to limit As solubility; however, colloids can maintain As mobility under such conditions.

We investigated colloid-mediated As transport in the Cobalt–Gowganda mining district (Ontario, Canada), which was once the largest silver mining camp in the world. Pedons developed on the tailings are composed of both Fe-rich, organic-poor soils dominated by scorodite, and organic-rich, Fe-poor soils where calcium (Ca) and organic matter (OM) stabilize colloids. Size-resolved fractionation reveals that As is strongly enriched in fine colloids (20 nm–0.45 µm) in soil leachates, whereas surface waters contain colloids of both the fine and coarse fractions (0.45–5 µm). Fine colloidal As showed strong positive correlations with OC ($r = 0.70$, $p < 0.01$) and ζ-potential ($r = 0.68$, $p < 0.01$), indicating that organic coatings and electrostatic stability promote the persistence of nanoparticulate As. In contrast, coarse colloidal As correlated with higher pH ($r = 0.43$, $p < 0.01$) and less negative ζ-potentials, consistent with Ca-bridging and pH-driven charge neutralization that promote aggregation into larger flocs.

TEM–EDS indicates two types of colloids: Fe-rich colloids with As concentrated in mineral–organic matter associations (MOA), and OM-rich colloids with As and Ca co-distributed in organic shells. EELS analyses indicate that the polarity of organic-functional groups (i.e., the proportion of C=O and C–O groups) increases from the organic matrix depleted Fe and As to interfaces with Ca-As-rich areas and to interfaces with Fe-As-rich areas. Arsenic K-edge EXAFS shows the predominant occurrence of Fe-arsenate bonding environments in Fe-rich colloids and mixed arsenate–carbon/arsenite-carbon bonding environments in OM-rich colloids. The latter two observations suggest that an increase in polarity towards Fe-arsenate and Ca-arsenite-rich areas leads to the stabilization of carbon, As(V) and As(III) species. In summary, these results establish a dual pathway for As transport under near-neutral conditions: Fe-rich colloids of low zeta potential sequester and thus immobilize As(V), whereas Ca–OM colloids of high zeta potential form nanoparticulate, mobile carriers of As(III) and As(V). This helps us understand how nanometric MOAs control colloid stability and As mobility. It also explains why neutral and carbonate-buffered environments can sustain high As mobility despite low bulk solubility. The findings have broad implications for predicting and managing As risks in mining-impacted catchments and karst systems worldwide.

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# Phytoremediation of Cd-Contaminated Soil: Role of Tropical Grasses in Modulating Cadmium Speciation

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**ABSTRACT**

Understanding the mechanisms regulating cadmium (Cd) availability in the soil–plant system has become increasingly relevant, especially in agricultural environments where Cd accumulation threatens food safety and soil health. As phytoremediation is a potential alternative to remove Cd from the soil it is important to understand the factors driving soil Cd availability to potentialize phytoremediation efficiency. Soil Cd availability depends largely on its chemical speciation, which is influenced by soil pH, redox potential, organic and inorganic ligands, competition with other cations and plant species cultivated in the polluted area. This research investigated the chemical speciation of Cd in soil solutions extracted from Cd-enriched soils cultivated with various grass species for phytoremediation purposes. Samples of a Cd-contaminated dystrophic Oxisol (7.5 mg Cd $kg^{-1}$ soil) were maintained at field capacity, and the resulting soil solutions were collected and analyzed for their chemical composition. Cadmium speciation was modeled using the Visual MINTEQ 4.0 software. The simulations revealed that Cd in the soil solution occurred predominantly as free $Cd^{2+}$ ions, followed by complexes associated with fulvic acids (FACd(aq) and $FA_2Cd^{+}G(aq)$) and chloride species ($CdCl^{+}$). Grasses with greater biomass production significantly influenced both the total Cd concentration and the distribution of its chemical forms in solution. The highest concentrations of $Cd^{2+}$ were observed in soils planted with *Andropogon gayanus* cv. Planaltina and *Brachiaria brizantha* cv. Piatã. In contrast, soils cultivated with *Brachiaria* species generally exhibited higher proportions of Cd complexed with fulvic acids, whereas inorganic Cd species were more prevalent in soil solutions from treatments with *A. gayanus* cv. Planaltina and *Sorghum sudanense*. Variations in pH and ionic composition of the soil solution induced by different grass species were key factors affecting Cd speciation and plant uptake, ultimately influencing biomass yield. Consequently, *Brachiaria* species are suggested as effective candidates for reducing Cd availability in soils through complexation with humic substances, while *A. gayanus* cv. Planaltina and *S. sudanense* may increase Cd mobility, making them less suitable for remediation of contaminated sites.

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# The Effect and Mechanism of Large-Scale Polymer Materials in the Remediation of Soil Chromium Pollution

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**ABSTRACT**

With the development of technology, environmental functional materials for heavy metal pollution remediation are emerging one after another, and the main direction of development is nanotechnology. The application of nanotechnology in water environments has been well supported by extensive data, but its performance in other environmental media (such as soil and sediment) is often limited by its own properties. As a result, large-scale macroscopic materials are gradually emerging and showing impressive effects. This report will discuss the applicable scenarios, application points, and application examples of three large-scale polymer materials in the remediation of soil chromium (Cr) pollution. By preparing millimeter-sized polyaniline/polyvinyl alcohol/sodium alginate composite materials (PPS) for soil remediation, a single application of this material can achieve a significant effect of removing 24.2% and 52.5% of total Cr and hexavalent chromium (Cr(VI)) from the soil, respectively. Additionally, the material exhibited excellent performance, maintaining over 95% removal efficiency of Cr in solution even after four cycles of use [1]. We further prepared porous large-scale functional polymer materials PAP by combining amyloid fibrils with polyethyleneimine (diameter approximately 5~6 mm). The obtained materials can simultaneously remove multi-heavy metals, and the adsorption capacity for Cr(VI) was as high as 121.4 mg/g, being comparable to or superior to the adsorption effect of many nanomaterials [2]. Lately, we developed an ascorbic acid-based polymer material APP, and the material not only exhibited excellent Cr removal over wide pH ranges (pH 2-11) [3], but also transformed the residual Cr to the reducible fraction and continuously transferred it to the material for fixation. These results deepen our understanding of the applicability and sustainability of large-scale functional materials in environmental remediation.

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# Effect of 5-year continuous phosphogypsum application on soil quality, heavy metal accumulation, and maize growth

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**ABSTRACT**

The application of phosphogypsum to saline soils has been recognized as an effective strategy to enhance crop productivity and alleviate salt-induced stress. However, it remains unclear whether repeated phosphogypsum application may lead to the accumulation of heavy metals in soil and maize grains, thereby posing a potential risk to human health. This study aimed to assess the health risks associated with heavy metals in a soil–maize (Zea mays L.) production system that received continuous phosphogypsum application for five years at varying rates (0, 1500, 3000, 4500, and 6000 kg·hm$^{-2}$). The total concentrations of As, Cd, Pb, Cr, and Hg were analyzed in phosphogypsum, soil, maize stalks, and grains. Results indicated that phosphogypsum application at rates up to 6000 kg·hm$^{-2}$ did not cause significant heavy metal contamination in soil, stalks, or maize kernels. phosphogypsum application also reduced soil pH, promoted the formation of larger soil aggregates, improved soil structural stability, and enhanced maize growth. Thus, at 6000 kg·hm$^{-2}$, maize yield increased by 5.1% compared to the control group.

**Acknowledgments**

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# Ascorbic Acid-Based Gel for Remediation of Chromium-Contaminated Soil

**ABSTRACT**

Soil contamination with hexavalent chromium (Cr(VI)) poses serious risks to ecosystems and human health due to its high toxicity and mobility. Conventional remediation techniques often face limitations such as difficulty in material recovery, incomplete metal removal, or adverse effects on soil microbiota. In this study, a novel bulk material (APP) composed of polyvinyl alcohol (PVA), polyethyleneimine (PEI), and ascorbic acid (AA) was developed and evaluated for its effectiveness in remediating Cr(VI)-contaminated soil.

The APP material was applied to contaminated soil at dosages of 1 wt% and 3 wt% over a 120-day period. Results demonstrated that the 3 wt% treatment achieved a Cr(VI) removal rate of 64.82% and a total Cr removal of 17.11% (312.47 mg/g APP) by 120d, with stabilization observed after 45 days. The material showed good stability, with minimal Cr leaching upon washing. BCR sequential extraction revealed a decrease in water-soluble and residual Cr fractions, indicating effective activation and removal of Cr rather than mere immobilization.

Physicochemical analyses (FTIR, 2D-COS, SEM-EDS, XPS) indicated that Cr(VI) was reduced to Cr(III) and adsorbed onto APP via functional groups such as -OH and -CO-NH-. Microbial community analysis showed that APP application reduced chromium stress, leading to a decrease in chromium-tolerant bacteria (*Bacillota, Pseudomonas*) and an increase in beneficial genera (*Arthrobacter, Rhizobium*). BugBase analysis further confirmed a reduction in stress-tolerant phenotypes and potential pathogens, indicating improved soil ecological health.

These findings suggest that APP is a promising, environmentally friendly material for the remediation of Cr(VI)-contaminated soils, combining high adsorption capacity, ease of recovery, and positive effects on soil microbial ecology.

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# Methylmercury Accumulation and Risk Mitigation in Chinese Paddy Soils

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**ABSTRACT**

A mean daily intake of 145.6 g per adult highlights the significance of rice as the primary dietary grain in China, and its role as the major route for human exposure to methylmercury (MeHg) – a neurotoxic compound that forms in paddies and bio-accumulates in rice grains. The low-oxygen anaerobic environment of paddy fields enhances the activity and conversion efficacy of Hg-methylating microorganisms, stimulating the *in situ* transformation of inorganic Hg into MeHg. The latter is the major pathway for MeHg accumulation in rice grains. Soils rich in clay and organic carbon have higher Hg holding capacity and a higher risk of MeHg transfer to rice crops.

Given the national background Hg content in soils averages 0.06 mg $kg^{-1}$ (range 0.03 to 0.1 mg $kg^{-1}$), Hg pollution in Chinese paddy soils is significant, with total Hg ranging from 0.012 to 150 mg $kg^{-1}$. Although no national dataset exists for MeHg, surveys suggested that Hg and MeHg concentrations ranged from 1.06 to 22.7 (mean 4.74) and 0.03 to 8.71 µg $kg^{-1}$ (mean 0.68), respectively, in rice grains. Higher Hg and MeHg levels occur in soils from southern regions (Guizhou, Guangdong, Hunan, Yunnan, Hainan) in relation to the industrial activities, coal combustion, and non-ferrous metal mining, while atmospheric deposition remains the primary pathway of Hg accumulation in soils. Besides, farming practices including fertilization schemes, wastewater irrigation, and straw return can either enhance or suppress MeHg accumulation in soils and its transfer to rice plants. Mitigation of MeHg risks in paddy soils includes application of biochar, sulfur, or iron oxide amendments to immobilize MeHg. Further, optimized water management or crop rotation can also suppress microbial methylation – practices that are crucial for sustainable rice production and public health protection in China.

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# Atmospheric Deposition and Trace Element Contamination in Urban Garden Soils and Vegetables in Kingston, New York (US)

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**ABSTRACT**

The contribution of atmospheric deposition to the contamination of vegetables and soils was studied in three urban vegetable gardens located in Kingston, New York (US) for As, Ba, Cd, Co, Cu, Ni, Pb, and Zn. Leaf Al was used as indicator of particle attachment or lodging. Surface and subsurface soil sampling was carried out along a cross-town transect and within gardens. Monthly atmospheric bulk deposition samples were gathered over one year and tested for trace element content. Experimental raised beds were built in each garden, consisting of 20 cm deep root pouches filled with imported loamy sand soil (pH 7.5-8.0; soil organic matter 16.5-17.0%). *Brassica oleracea var. acephala* (Winterbor kale) was grown in root pouches under three treatments featuring an increasing degree of specimen cover (imported soil only, and imported soil straw mulch with/without row cover). Leaves were sampled from the kale grown on the experimental beds after 110 d and from local supermarket specimens. Leaves were first washed with deionised water and then EDTA solution to distinguish the degree of particle adhesion and to account for local splash and redeposition. Root pouch soil was sampled at two depths (0-1 cm and 15-20 cm). Irrigation water, straw mulch, and imported soil were sampled prior to and following the field experiment.

Results showed a tendency for legacy soil Cu, Pb, Zn concentrations to be higher than recommended safe levels for New York State. Particle Al and trace element content correlated significantly, suggesting a common regional source. Raised bed soil trace element contamination was low, except Cu and Zn, owing to high amounts for those elements in straw mulch and imported soil. Irrigation water bore very low contaminant levels. Soil surface contamination levels decreased slightly with increasing cover. Straw mulch trace element content varied significantly only by location, suggesting local (intra-garden) sources. Kale exhibited low contamination levels except for Zn (median of 2.5 ppm), with values similar to those of supermarket specimens. Leaf Al concentrations correlated significantly with leaf trace element concentrations (particle lodging) except Cu and with both deionised and EDTA wash extractions (particle adhesion) except for As. Leaf As, Cd, Co, and Pb are inferred to be mainly from particle lodging and attachment by means of both atmospheric deposition and local redeposition. Leaf Ba, Cu, Ni, Zn are mostly explainable by uptake from imported soil. While the degree of contamination was generally very low for all trace elements except Zn (due principally to Zn-rich imported soil and straw mulch), increasing the extent of raised bed cover still allowed dust influx from both regional and local sources, and thereby some kale contamination.

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# Bioaugmentation effects of three ecological categories of wild earthworms on phytoextraction of Sedum plumbizincicola in Cd and Zn contaminated soils of South China

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**ABSTRACT**

Phytoremediation is a cost-effective solution for large-scale rehabilitation of contaminated soils, but its efficiency is often limited. Combining soil fauna, such as earthworm, with plants is a promising approach to enhance remediation. This study investigated the bioaugmentation effects of three ecological categories of earthworms (epigeic *Amynthas cortices, endogeic Amynthas robustus,* anecic *Amynthas aspergillum, and* anecic *Metaphire guillelmi*) on Sedum *plumbizincicola* in Cd- and Zn-contaminated mining soils at different contaminated levels under controlled laboratory condition for 90 days. We assessed physiological states and metals concentration in different tissues of *S. plumbizincicola,* and metals availability. Results indicated that earthworm introduction significantly promoted the vigorous growth of *S. plumbizincicola* and enhanced both its robustness and the soil phytoextraction efficiency. Specifically, the biomass of both aboveground tissues and roots was higher in inoculation *S. plumbizincicola* with earthworms *A. cortices, A. aspergillum*, and *M. guillelmi* than only cultural *S. plumbizincicola*. Earthworm activities increased Cd and Zn concentrations in the harvestable aboveground tissues by 5.95%-76.7% and 7.49%-20.8%, respectively. As for the ecological categories of earthworms, epigeic (*A. cortices)* and anecic (*A. aspergillum* and *M. guillelmi)* were particularly effective in enhancing soil nutrient mineralization and metal bioavailability, further promoting the transfer of metals from roots to aboveground tissues. The transfer factors of Cd and Zn increased by up to 98.3% and 110%, respectively. The highest plant biomass, metal concentrations, and metal uptake amounts of *S. plumbizincicola* were observed at the medium contamination level, roughly two to three times greater than at other levels. Furthermore, earthworm species within the same ecological category exerted distinct effects on metal bioavailability, which varied with contamination level. For instance, in medium-contamination soil, *A. aspergillum* increased metal concentration in soil solution through its burrowing and digestion activities, whereas *M. guillelmi* showed an opposite effect. However, in high contamination level, those two species of earthworm showed same trend of reducing the influence, especially *A. aspergillum*. Its suggests that earthworms employ trade-off strategies between survival and growth in metal-stressed environments. Random forest analysis identified aboveground biomass as the dominant factor in enhancing phytoremediation, followed by metal transfer capacity, available phosphorus, and alkali-hydrolysable nitrogen. In conclusion, earthworms, especially epigeic and anecic species, can effectively enhance the phytoextraction of metals by *S. plumbizincicola*, with remediation efficiency being species-specific. This study provides insights into the synergistic use of hyperaccumulators and soil fauna for rehabilitating multi-metal polluted soils, offering a viable strategy for environmental restoration.

**Keywords:** Phytoremediation; Cd and Zn, earthworm ecological category; Sedum *plumbizincicola*; Diffusive gradients in thin-films (DGT);

# Particle-nanoparticle transformations in metal-contaminated soils

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**ABSTRACT**

Metals are often released into soil through atmospheric deposition of micrometer-sized particles. Common sources of metal-bearing particles include industrial activities (e.g., smelters), traffic, mine waste, and urban activities (e.g., house paint). In contrast, leisure activities, such as shooting ranges, do not contribute similar amounts of metal-bearing particles. In all these cases, the weathering of the deposited micrometer-sized particles results in their transformation into metal-bearing incidental nanoparticles (NPs). The formation of these incidental NPs is governed by the slower dissolution kinetics of the micrometer-sized phases relative to their faster precipitation kinetics. Combining focused ion beam and ion mill technologies with transmission electron microscopy reveals that these particle-to-nanoparticle transformations can be highly complex, involving the formation of different generations of nanoparticles and unexpected phases not commonly observed in soils. For example, wind-blown transport and deposition of chalcopyrite-related phases ($CuFeS_2$) from a mine waste pile onto nearby soils lead to their transformation into covellite (CuS) and chalcocite ($Cu_2S$) NPs within soil organic matter (SOM), a process commonly seen during the supergene enrichment of copper in ore deposits[1]. Emission and deposition of Zn-Fe-oxides on smelter-affected soils result in the formation of euhedral NPs of spinel phases like franklinite ($ZnFe_2O_4$) and Zn-bearing magnetite on SOM and clay mineral surfaces[2]. Deposition of micrometer-sized Pb-Cr-Zn-Ti-bearing paint flakes onto residential soils results in the formation of multiple NP generations, including hexavalent Cr-bearing phases such as crocoite, $PbCrO_4$, and phoenicochroite ($Pb_2CrO_5$)[3]. Finally, the weathering of metallic Pb and Sb phases in micrometer-sized gunshot residues from a shooting range produces a complex assemblage of numerous Pb- and Sb-bearing NPs[4]. In all these cases, the transport and bioaccessibility of metals released during the weathering of micrometer-sized particles are strongly influenced by the stability of their respective incidental NPs (considering solubility and aggregation) and the matrices in which these NPs form.

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# Soil Trace Elements and Human Health

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**ABSTRACT**

The adage "we are what we eat" underscores the profound connection between human health and the natural resources we depend on—soil and water. This presentation explores the dual role of trace elements in human health, emphasizing essential nutrients (iron, zinc, and selenium), toxic heavy metals (cadmium), and their complex interplay. While the Green Revolution of the 1960s revolutionized agriculture through semi-dwarf crop breeding, boosting global grain yields, it inadvertently reduced essential mineral concentrations in staple crops like rice and wheat, contributing to widespread micronutrient deficiencies. Focusing on selenium, our multi-center cohort study (N=36,000 participants) revealed a significant positive correlation between serum selenium levels—linked to regional soil selenium content—and diabetes prevalence across China. This suggests that selenium supplementation in most Chinese regions may elevate health risks rather than confer benefits. For toxic elements, a soil-rice-human cohort study (N=1,500) demonstrated that cadmium-contaminated soils elevate dietary cadmium exposure, increasing risks of kidney dysfunction, gut microbiota disruption, and liver cancer. Critically, we identified dynamic interactions between essential and toxic elements across the soil-food-human continuum, with implications for nutrient absorption, toxicity mitigation, and disease susceptibility. These findings underscore the urgency of adopting a One Health framework—integrating agricultural, environmental, and public health strategies—to address micronutrient deficits and heavy metal toxicity holistically. By balancing crop productivity with nutritional quality and environmental safety, such approaches can safeguard human health while promoting sustainable ecosystems.

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# Heavy Metal Immobilization Potentials of Some Agricultural Wastes in Contaminated Arable Soil

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**ABSTRACT**

Soil pollution, particularly heavy metal contamination, poses a critical environmental challenge with implications for human health and ecosystems. This study investigated the potential of agricultural waste materials: Cassava peel (CP), Conventional charcoal (CC), Maize husk (MH), Maize stover biochar (MSB), Oilpalm frond biochar (OFB), and Rice husk (RH) to immobilize heavy metals in contaminated soils and to identify the most suitable immobilization agent.

A neutral loamy sand arable soil (pH 7.34), sampled in 1 kg portions in triplicate, was spiked with intervention levels of selected heavy metals (Cd - 380, Cr - 240, Ni - 720, and Pb - 210 mg $kg^{-1}$). Each soil sample was amended separately with an equivalent of 10 t $ha^{-1}$ of the respective additive before being packed into leaching columns. The columns were watered with 100 ml of distilled water at 7-day intervals for 90 consecutive days. Heavy metal concentrations in both leachate and soil samples collected from each column were analyzed to evaluate the efficiency and capacity of the immobilization agents.

The results showed that heavy metal retention in the soils depends on the additives. Control had significantly higher values compared to most other amendments, with the lowest values observed in CP (155.60 mg $kg^{-1}$ Cd), MH (4.23 mg $kg^{-1}$ Cr and 174.37 mg $kg^{-1}$ Ni) and CC (83.43 mg $kg^{-1}$ Pb). In the leachates, RH, MH, CP, and CC showed the highest concentrations of Cd, Cr, Ni, and Pb, respectively. MH had significantly low immobilization efficiency for Cd (4.85%) and Pb (7.55%) but highest for Cr (97.92%) and Ni (49.75%) with OFB and CC respectively exhibited significantly higher values for Cd (42.91%) and Ni (61.64%). The additives did not differ distinctly in their immobilization capacities, except for MH, which had the lowest values for Cd (190.51 mg $l^{-1}$) and Pb (113.40 mg $l^{-1}$), whereas CC and OFB showed better capacities. Overall, the immobilization potential of the additives was ranked as OFB > CC > RH > MH > MSB > CP > Control while the immobilization capacity was as OFB > Control > CC > RH > MSB > MH > CP. Biochar portrayed a better potential in heavy metals immobilization particularly in a neutral soil condition.

**Key words**: Additives, Capacity, Efficiency, Heavy metals, Immobilization.

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# Quantification of chromium and nickel lateral migration in serpentine soils via ion, colloid and particulate pathways

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## ABSTRACT

Serpentine soils represent critical natural reservoirs of chromium (Cr) and nickel (Ni), posing substantial environmental threats through metal lateral migration into surrounding ecosystems. While conventional views emphasize ionic migration as the dominant pathway for Cr and Ni, the role of colloidal migration remains overlooked. In this study, we systematically investigated mineralogy, chemical speciation, colloidal characterization, and migration modeling of Cr and Ni along a typical serpentine toposequence, to achieve a comprehensive understanding of the driving mechanism for their lateral migration via ionic, colloidal and particulate pathways.

Characterization of soil colloids by field flow fractionation and scanning transmission electron microscope showed that colloidal Cr and Ni mainly coexisted with Fe-oxides. Fe-oxide colloids were identified as the primary carriers for colloidal Cr and Ni migration from soil to aqueous phase, whose formation was governed by low pH, high organic matter (OM) and Fe-oxide mineralogy. Quantitative analysis of migration pathways revealed that Cr migrated from soil to water primarily in colloidal Cr(III) (53-79%), with Cr(VI) ions as a secondary pathway, whereas Ni migration was dominated by ionic form (73%-94%). Path modeling indicated that Cr migration was strongly driven by Mn-oxide-mediated Cr(VI) formation and modulated by soil OM and pH. In contrast, colloidal Cr was stably hosted in Fe colloids with little variation along the toposequence, making its migration dependent on Fe colloid mobility. For Ni, weathering enhanced ionic migration but reduced colloidal migration by promoting Ni release from Fe-oxides.

These findings challenge conventional paradigms by establishing colloidal Cr(III), rather than Cr(VI), as the dominant migration pathway, highlighting the crucial yet overlooked role of colloidal migration in heavy metal dispersion. This study provides a quantitative framework for understanding Cr and Ni lateral migration in serpentine environments, contributing to more accurate risk assessment and management strategies.

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# Long-Term Effects of Repeated Organic Amendment Applications on Cadmium Bioavailability: Insights from a Five-Year Pot Experiment

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**ABSTRACT**

Understanding the long-term effectiveness of amendments and the mechanisms of metal immobilization is essential for managing cadmium (Cd) contamination in agricultural soils. Although short-term studies (1-2 years) dominate the literature, the cumulative effects of repeated organic amendment applications are poorly documented. Past industrial activities in Belgium have led to widespread low-level soil contamination (< 1 to 5 $mg \cdot kg^{-1}$ Cd), raising concerns about food safety as excessive Cd levels have been found in vegetables from private and market gardens. A five-year pot experiment (2020-2025) was conducted using soil from a contaminated market garden in the Province of Liège, Belgium (pseudo-total Cd: 1.5 $mg \cdot kg^{-1}$, initial pH $CaCl_2$: 5.6). The pots (5L capacity, five replicates) initially received control, biochar and green waste compost treatments. In 2021, lime was added as a fourth treatment. The amendments were reapplied each spring and Swiss chard was cultivated outdoors annually, with systematic monitoring of soil pH and $CaCl_2$-extractable metals. Green waste compost showed the most significant and persistent increase in pH. A marked pH rise and a sharp decline in $CaCl_2$-extractable Cd occurred after the second compost application. Subsequent annual applications primarily maintained and stabilized these effects. Biochar induced more gradual changes in pH and Cd. No significant effects were observed during the first year across all amendments. Lime addition also increased soil pH, though to a lesser extent than compost. Significant interactions were identified between lime and the other amendments, which complicates the interpretation of the overall effects of the treatments. Compost reduced Cd bioavailability beyond the effect of pH alone, likely through the enrichment of soil organic matter and increased cation exchange capacity. After five years, most compost-amended plants fell below the European food safety standards, showing that plant Cd responds slowly and requires long-term amendment applications. Unlike field conditions, pots exhibited stable, monotonic trends with minimal seasonal fluctuations in pH or $CaCl_2$-extractable Cd. This stability reflects the controlled irrigation regime and the limited, enclosed root environment. Furthermore, plants grown in pots produced significantly lower biomass than field-grown crops, highlighting the necessity of field experiments to validate these observations under realistic agronomic conditions. Even in pots with very low $CaCl_2$-extractable Cd and near-neutral soil pH, vegetable Cd concentrations occasionally exceeded European limits, demonstrating that low soluble Cd alone does not guarantee food safety. This five-year study shows that repeated applications of organic amendments progressively reduce Cd bioavailability, with green waste compost yielding the strongest results. However, achieving stable improvements in soil pH and Cd immobilization requires 2 to 3 years of repeated applications.

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# Managing Cadmium Uptake in Vegetables with Repeated Applications of Amendments: Lessons from a Multi-year Field Experiment

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**ABSTRACT**

Food safety has become a major concern in Belgium due to excessive cadmium (Cd) levels in vegetables grown in private and market gardens, even in areas with low soil contamination (< 1 to 5 mg·kg$^{-1}$ Cd). Past industrial activities in central Belgium, particularly in the Meuse-Vesdre valleys, caused significant atmospheric depositions that continue to affect food production today. Although the role of soil pH in controlling Cd mobility and plant uptake is well established, achieving neutral or slightly alkaline pH appears insufficient to ensure compliance with European food safety standards under these low-level contamination scenarios. A three-year field experiment (2023-2025) was conducted in two market gardens in the Province of Liège, with pseudo-total soil Cd levels of 1–2.5 mg·kg$^{-1}$ and initial pH of approximately 5.5. Using a randomized complete block design with three to five replicates, four treatments were established: control, lime application (marine-derived $CaCO_3$), biochar amendment and green waste compost amendment. Swiss chard and lettuce were cultivated over several seasons. Soil samples were collected seasonally to measure soil pH and $CaCl_2$-extractable metal concentrations, while edible tissues were analyzed for total metal content. Compost application significantly increased soil pH compared to control, sometimes exceeding lime addition, and substantially reduced $CaCl_2$-extractable Cd. Lime also increased pH effectively, while biochar demonstrated more moderate effects. However, no significant amendment effects were observed during the first year, suggesting that repeated applications are necessary before measurable impacts on Cd bioavailability emerge. Strong seasonal variability in soil pH and $CaCl_2$-extractable Cd levels was observed across years, independent of the effects of amendments. This highlights the influence of environmental factors (temperature, moisture, etc.) on plant biomass production and metal mobility. Despite substantial increases in soil pH (often exceeding 6.0) and reductions in extractable Cd in amended plots, analyses of vegetables suggest that achieving compliance with the EU limits remains challenging. Both Swiss chard and lettuce frequently exceeded regulatory thresholds. These results highlight the limitations of conventional pH-based remediation strategies in low-contamination contexts. Geochemical modeling is essential for elucidating Cd speciation in soil solution and identifying additional immobilization mechanisms beyond the effects of pH. Long-term, integrated approaches combining predictive modeling and temporal monitoring of multiple geochemical processes are necessary to ensure vegetable safety and develop effective, site-specific remediation strategies in low-contamination agricultural contexts.

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# Effects of plant growth-promoting bacteria and its mechanisms towards Brassica juncea L. growth and Cd phytoextraction

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**ABSTRACT**

In recent years, with the development of the global Microbiome Project, more and more microorganisms have been used to assist phytoremediation of heavy metal-contaminated soils. Numerous plant growth-promoting bacteria (PGPB) have been verified to play a beneficial role in promoting plant growth and facilitating heavy metal uptake of their host plants, which consequently improved phytoremediation efficiency. However, little is known about the functional mechanisms and application effects of these PGPB on the non-host plants with promising remediating potential. Here, 12 different PGPB strains isolated from a hyperaccumulator *Sedum alfredii* Hance were adopted to investigate their effects on *Brassica juncea* L. growth and Cd accumulation. The results showed that two strains, namely *Burkholderia* SaMR10 and *Sphingomonas* SaMR12 were identified as the promising microbes for oilseed rape to improve phytoremediation efficiency of Cd contaminated soils. Furthermore, the colonization pattern of SaMR12 was observed by a confocal laser scanning microscope, which showed SaMR12 entered the roots through the conjunction of taproot and lateral roots, and then was transported to stems and leaves. Cd exposure resulted in the damage of the antioxidant system in oilseed rape, which induced the production of hydrogen peroxide ($H_2O_2$), increased the content of malondialdehyde (MDA) and proline accumulation. Under Cd stress, SaMR12 inoculation could alleviate the Cd-induced damage of *B. juncea* by decreasing the concentrations of $H_2O_2$, MDA and proline, increasing the activities of antioxidative enzymes, and regulating the GSH-AsA cycle. Through these ways, SaMR12 inoculation facilitated plant growth and Cd accumulation of *B. juncea* under Cd stress, which further contributed to the elevated phytoextraction efficiency. In addition, inoculation of SaMR12 could alleviate Cd-induced damage and enhance plant growth by restoring photosynthetic activity and maintaining electron transport functionality. Simultaneously, the field experiment indicated that the combined application of PGPB strains was more effective towards oilseed rape growth and Cd phytoremediation. However, the investigation into its microbial ecological mechanisms showed that original ecological niches were not a major factor in the growth-promoting attributes, Cd phytoextraction efficiency and changes in bacterial community structure, suggesting ecological niche was not the primary determinant for effective bioaugmentation inoculants construction. The above results expanded the current knowledge about bacterial inoculation and provided fundamental guidance for the production of PGPB consortia as bioaugmentation agents in Cd-contaminated fields to further facilitate Cd phytoremediation and develop sustainable agriculture.

**Keywords:** cadmium; phytoextraction; plant growth-promoting bacteria; antioxidative response; photosynthesis; microbial community

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# Sulfur enhances iron plaque formation and stress resistance to reduce the transfer of Cd and As in the soil-rice system

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## ABSTRACT

Sulfur plays an essential role in agricultural production, but few studies have been reported on how sulfur simultaneously impacts the transformation of cadmium (Cd) and arsenic (As) in the soil-rice system. This research selected two soils co-contaminated with both Cd and As, varying in acidity and alkalinity levels, to study the impacts of elemental sulfur (S) and calcium sulfate ($CaSO_4$) on the migration and accumulation of Cd and As by rice. Results indicated that two types of sulfur had a substantial ($P < 0.05$) impact on decreasing the contents of Cd (28.3-50.4%) and As (20.1-38.6%) in brown rice in acidic and alkaline soils. They also increased rice biomass (29.3-112.8%) and reduced Cd transport coefficient (27.2-45.6%) significantly ($P < 0.05$). Notably, sulfur augmented the generation of iron plaque on rice root surfaces, which increased the fixation of Cd (17.6-61.0%) and As (14.0-45.9%). SEM-EDS results also indicated that the rice root surface exhibited significant enrichment of Fe, Cd, and As. The mechanism of simultaneous Cd and As immobilization by sulfur application was mainly ascribed to the contribution of iron plaque. Additionally, sulfur reduced the contents of Cd and As in soil porewater and promoted the transformation of As(III) to As(V) to reduce the toxicity of As. The K-edge XAFS of As in iron plaque also confirmed that sulfur application significantly promoted As(III) oxidation. Sulfur also promoted the activities of antioxidant enzymes and the contents of NPT, GSH, and PCs in rice plants. In general, this study establishes a foundation for sulfur to lower As and Cd bioavailability in paddy soils, enhance iron plaque and rice resistance, and reduce heavy metal accumulation.

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# Dual function of sulfur in Cd-As co-contaminated soils: enhancing phytoremediation with mustard and ensuring rice safety under drought-flood rotation systems

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## ABSTRACT

Sulfur can regulate cadmium (Cd) and arsenic (As) bioavailability in flooded paddy field. However, in classical drought-flood rotation systems with alternating redox conditions, the geochemical behavior of Cd and As under sulfur amendment remains uncertain. This study investigated the dual effects of sulfur in a mustard-rice rotation system and its impact on the migration and transformation of Cd and As crop production safety. The results showed that sulfur application during the upland season significantly boosted Cd and As bioavailability, enhancing the hyperaccumulator mustard's ability to extract heavy metals. Specifically, the Cd and As contents increased by 31.8%-35.5% and 17.1%-25.2% in the aboveground, and by 43.0%-44.1% and 33.1%-36.5% in the underground. Additionally, mustard's antioxidant system was significantly improved, leading to a 12.6%-14.8% increase in biomass. During the paddy season, residual sulfur from the mustard season significantly reduced Cd and As bioavailability and mobility by promoting the formation of iron plaque on rice roots. Consequently, Cd and As contents in brown rice decreased by 48.4% and 45.8%, respectively, with Cd meeting the requirement of quality safety standards. Microcosm experiments confirmed a distinct interaction between sulfur application and water management: sulfur enhanced heavy metal mobilization under drought conditions, while drastically reducing their bioavailability under flooded conditions. To summarize, sulfur enhances heavy metal accumulation during the mustard season for "pollution remediation" and ensures "safe production" during the rice season by blocking the absorption of heavy metals. The proposed sulfur-mediated "remediation-production" mustard-rice rotation system offers a sustainable and efficient remediation strategy for Cd-As co-contaminated soils.

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# Combining multiple high-resolution in-situ techniques to understand the metals mobilization at anoxic-oxic interfaces in flooded industrial soils

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**ABSTRACT**

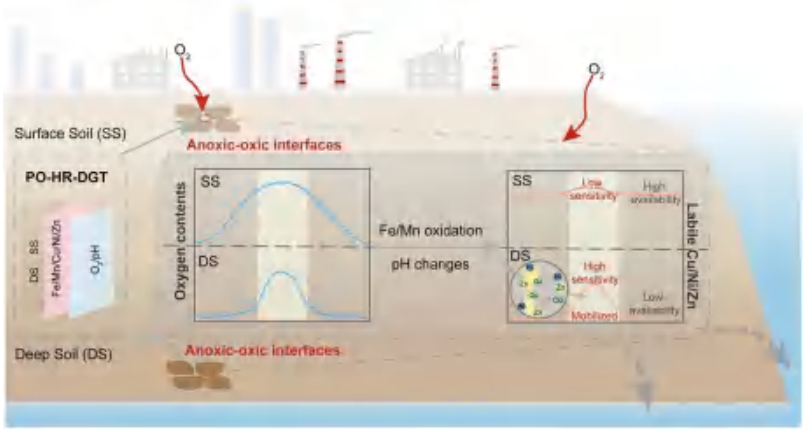
Industrial sites in coastal cities experience fluctuating redox conditions driven by climate change, forming anoxic-oxic interfaces and influencing the availability of heavy metals (HMs). What remains elusive is how oxygen contents influence the formation of anoxic-oxic interfaces and HMs mobilization in industrial soils with varying physicochemical properties. Here we investigated the mobilization mechanisms of HMs (Fe, Mn, Cu, Ni, and Zn) at anoxic-oxic interfaces in different depths soils at a historical industrial site using high-resolution in-situ techniques, including planar optodes (PO) and diffusive gradients in thin-films (DGT). The PO accurately captured O2 and pH distributions, revealing greater $O_2$ diffusion in surface silty loam soil compared to deep silty clay loam soil. Results showed distinct redox-mediated HMs mobilization patterns between surface and deep soils. Surface soils exhibited rapid Fe(II)/Mn(II) oxidation, yet Cu, Ni, and Zn remained relatively stable due to higher contamination and DOC content. Conversely, deep soils displayed significant Cu, Ni, and Zn mobilization at anoxic-oxic interfaces, correlating to the changes of $O_2$ and pH. These findings demonstrate the critical role of soil properties and microscale redox dynamics in controlling HMs behavior, offering valuable insights for managing contaminated industrial sites.

**Keywords:** Redox microzones, Different soil properties, In-situ sampling, High-resolution visualization, Heavy metals availability

**Highlights:**

a) Anoxic-oxic interfaces simulated in varying depth industrial soils.
b) PO-HR-DGT enabled in-situ 2D microscale multi-parameter mapping in industrial soils.
c) Surface soils showed Fe/Mn oxidation but stable Cu, Ni, and Zn labile concentrations.
d) Deep soils exhibited significant Cu, Ni, and Zn mobilization at anoxic-oxic interface.
e) Soil properties could govern redox driven metal behavior under climate fluctuations.

**ABSTRACT graph:**




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# IAA-producing and Cd-tolerant endophyte Bacillus sp. RE35 enhance Cd trap in rice roots via root cell wall remodeling during colonization

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**ABSTRACT**

Cadmium (Cd) accumulation in rice poses a significant threat to food safety and human health. Plant growth-promoting endophytes (PGPEs) offer a promising strategy to mitigate Cd stress. Yet, the mechanisms underlying microbe-mediated reduction of Cd uptake, particularly through specific plant-microbe interactions, remain poorly understood. Here, we demonstrate that the root endophyte Bacillus sp. RE35, a Cd-tolerant and high-IAA producer isolated from rice, established an effective apoplastic niche and significantly enhanced Cd retention in roots through a multi-level mechanism. Successful colonization of RE35 in the root apoplast, confirmed by the red fluorescent protein labeling, strain-specific gene quantification and colonization-related genes analysis, promoted extensive root morphological remodeling via both de novo and salvage pathways of IAA biosynthesis under Cd stress. Notably, RE35 inoculation drastically reshaped Cd distribution, increasing cell wall-bound Cd by 64.7% while reducing shoot Cd accumulation by 24.1-49.7%. This enhanced apoplastic trapping of Cd was attributed to a comprehensive cell wall remodeling program, activated through RE35-induced expression of plant receptor kinases (e.g., LRR-RLKs, LysM-RLKs) and the upregulation of key genes involved in the biosynthesis of pectin, hemicellulose, and lignin. In parallel, RE35 modulated host Cd transport by downregulating influx transporter genes (OsNRAMP5, OsZIP5/9) and upregulating the vacuolar sequestration gene OsHMA3. Our findings reveal a Cd-responsive regulatory network where endophytes enhance apoplastic immobilization by coordinating auxin signaling, receptor kinase activation, and cell wall remodeling, providing a mechanistic basis for sustainable agriculture in contaminated environments.

**Acknowledgments**

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# A Basin-Scale Synthesis of Inorganic Contamination Across Slovenia's Major Floodplains

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**ABSTRACT**

In Slovenia, metal-rich lithologies align with a long industrial history, and the increasing frequency of flood events caused by climate change is remobilizing potentially toxic elements of both geogenic and anthropogenic origins. Floods mobilize and redistribute metal-contaminated sediments, affecting soil functions, degrading farmland, and altering human exposure pathways. This study offers a comprehensive basin-scale synthesis of inorganic contamination (primarily Pb, Zn, Cd, Hg) in soils and sediments on floodplains across Slovenia's four main river basins (Sava, Drava, Mura, Soča). National and international monitoring data, published geochemical datasets, and literature were integrated with GIS-based spatial analysis, combining geological, pedological, hydrological, land-use, and flood hazard layers to quantify the overlap between contamination sources and flood-prone areas. Results reveal a recurring pattern: historical mining and smelting have transformed natural ore deposits into persistent hotspots. The industrialized Sava Basin hosts multiple sources, including the former Celje Zn smelter, the Jesenice steelworks, and the Litija Pb–Hg district, with overbank sediments locally exceeding background concentrations by several orders of magnitude. The Drava Basin is dominated by the Meža Valley Pb–Zn–Cd plume exported to Croatia. The agricultural Mura Basin is characterized mainly by geogenic As and diffuse Cd. The Soča Basin continues to be affected by the Idrija mercury mine, which was historically one of the world's largest and released large quantities of mercury into the environment. Significant amounts of mercury remain stored in floodplain sediments, and ongoing transport via the river system ensures that it continues to reach the Adriatic Sea. Climate change-induced intensification of extreme flooding, such as the 2023 event affecting 86% of Slovenian municipalities, increases contaminant remobilization and associated health risks. Slovenia thus serves as an example of how legacy metal pollutants persist and re-enter fluvial systems under changing climate conditions. These findings emphasize the urgent need for accelerated remediation of key hotspots, secure containment of historical waste, systematic sediment and floodplain monitoring, and sustained transboundary collaboration.

**Acknowledgments**

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# Chemical Remediation of Multi metal Contaminated Inceptisol by Valorizing Calcitic and Lignocellulosic Wastes

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## ABSTRACT

The Eastern Metropolitan Municipal Solid Waste (MSW) Landfill Complex, bordering the East Kolkata Wetlands (Ramsar Site 1208, India), represents a critical anthropogenic hazard. Long-term disposal of MSW and sewage irrigation in the adjacent agro ecosystem have compromised the native Inceptisol. Pb, Cr and Zn concentrations have surpassed the maximum permissible limits (mg/kg) for agricultural soils set by the World Health Organization (WHO). Spatial mapping of dehydrogenase activity (DHA) revealed a pronounced heterogeneity identifying suppressed soil microbial functioning. While some rhizosphere pockets exhibited strong activity, majority of the sites remained below 10µg TPF (triphenylformazan)/ml and ~15% showed undetectable DHA (<1µg/ml), suggesting widespread metabolic inhibition due to metal toxicity. A significant portion of metals remained as labile fractions after sequential extraction using Tessier's method, suggesting a high risk of bioavailability.

Waste-derived adsorbents were studied to rehabilitate this matrix; screening against commercial zeolites (positive control) identified washed eggshell (ES) and sawdust (SD) as superior candidates, with ES exhibiting removal efficiency comparable to the zeolite benchmark (>96%). Their regeneration potential was also confirmed across 3 consecutive cycles. Response Surface Methodology (RSM) based on a Box–Behnken Design (BBD) was used to optimize batch adsorption parameters. The quadratic model for SD ($R^2 = 0.90$; $p = 0.04$) identified pH 6.0 and a dose of 0.5g as optimal for Pb(II) removal**(Fig.1)** while exhibiting enhanced selectivity for Cr(III) in ternary systems. ES functioned as a "super-adsorbent" for Pb and Zn, achieving >99% removal.

Building on optimized parameters, pot experiments evaluated treatment efficacy using spinach (*Spinacia oleracea*) to assess food safety benefits and Indian mustard (*Brassica juncea*) for stabilization efficiency. The assessment included labile metal fractions, leachate and biological response monitoring. Results confirm that the amendments significantly reduced metal bioavailability and were accompanied by a statistical resurgence of DHA and actinomycetes populations. This study establishes an economical protocol converting local waste into soil amendments, demonstrating that optimized ES and SD, effectively stabilize metals and restore soil biological functions.

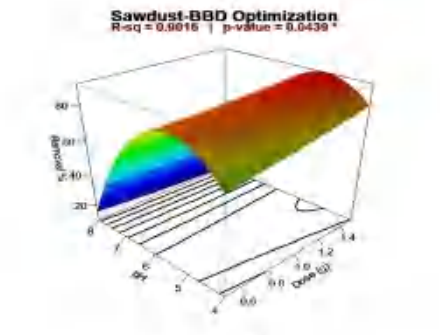



**Fig.1.** 3D Response Surface plot for Sawdust-BBD optimization

**Keywords:** MSW Landfill; Waste Valorization; Metal Immobilization; Box Behnken Design; Soil Enzymes.

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# Quantifying Metal Transport by Water Erosion: A Field-Based Assessment in a Semiarid Mediterranean Former Mining Area (SE Spain)

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**ABSTRACT**

This study presents a water-erosion use-case within the broader soil-pollution project SOILPROM, aiming to quantify the dispersion of metals and metalloids driven by storm-generated runoff in the former mining district of La Unión–Sierra de Cartagena (SE Spain). The upper Rambla del Beal drains a landscape heavily contaminated by century-long mining activities, where sediments originate from several types of metalliferous mine wastes. In the upper channel, soils show extremely high metal(loid)s concentrations (e.g., As up to 650 mg $kg^{-1}$, Pb and Zn frequently above 10,000 mg $kg^{-1}$, Cu commonly >100 mg $kg^{-1}$, Mn often >1,500 mg $kg^{-1}$, and Cd between 10–100 mg $kg^{-1}$.

Field monitoring is conducted along ~1.5 km of the upper El Beal wadi, where three flow-regulating dams intercept stormwater and sediment. Their contributing sub-catchments were delineated as 4 ha, 33 ha, and 19 ha. To quantify sediment deposition, 69 erosion nails were installed across the waterbed. The initial height between the ground surface and the top end of each erosion nail was measured before the monitoring period. After each storm event, the height was measured again, and the difference relative to the pre-storm measurement yielded the amount of sediment deposited Core samples were extracted beside selected nails and inserted to the depth of accumulated sediment, previously determined from nail measurements.

To characterise runoff, 14 PVC pipes per dam, perforated at heights between 5 and 50 cm, were installed to collect stormwater and transported sediments. Water samples were analysed for pH, electrical conductivity, and dissolved metals, and sediments for grain size, pH, salinity, and total metal content. Maximum water marks on dam walls enabled estimation of runoff volumes.

Catchment-scale parameters (slope, vegetation cover, surface stoniness, soil pH, salinity, metal content, texture, structure) were assessed to explain erosion responses. The first results reveal strong contrasts in sediment yield among dams, driven by differences in catchment morphology and substrate properties.

The observed metal dispersion poses a significant environmental risk: runoff is often highly acidic, enhancing the solubility and mobility of metals, while sediments display elevated concentrations of As, Pb, Zn, Cd, Cu, and Mn. These factors strongly increase the potential for downstream transport and ecological exposure during storm events. These integrated measurements provide the basis for quantifying metal dispersion under varying storm magnitudes and for supporting forthcoming hydrological and sediment-transport modelling, and the design of remediation measures.

**Acknowledgments**

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# Stabilizing Urban Soil Lead: Long-Term Effects of Soil Amendments on Bioaccessibility and Speciation

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**ABSTRACT**

Urban soil contaminated with lead (Pb) from various sources poses a significant environmental health risk, particularly increasing Pb exposure among young children. Soils in Kansas City, Missouri, have reported Pb levels ranging from background to alarmingly high levels, similar to those in other older cities. This three-year field study aimed to reduce Pb bioaccessibility and to identify the underlying mechanisms by using affordable phosphate-based amendments that promote the formation of sparingly soluble Pb-phosphate minerals. The reduction in bioaccessible Pb was evaluated after in situ incorporation of five soil amendments (selected from a laboratory incubation study) at three vacant lots with total Pb concentrations ranging from 60 to 800 mg $kg^{-1}$. A modified physiologically based extraction technique (PBET) simulating the gastric dissolution process was used to determine Pb bioaccessibility, along with an in vitro bioaccessibility assay (IVBA) at pH 2.5. Soil Pb speciation was determined using X-ray absorption spectroscopy data collected at the Stanford Synchrotron Radiation Light Source, and soil Pb fractionation was determined using a sequential extraction procedure. At Site 1, a significant reduction in bioaccessible Pb, as measured by PBET, was evident one month after amendment incorporation and continued thereafter, with ammonium polyphosphate (APP) achieving a 35% reduction and Class A biosolids a 20% reduction compared to the untreated control. Although bioaccessible Pb results from the PBET extraction showed a significant treatment effect, the IVBA extraction did not ($p < 0.05$), indicating that the PBET method is more sensitive in detecting treatment effects due to its extraction solution chemistry. The other two sites (2 and 3) did not show immediate reductions in bioaccessible Pb, likely due to their low total Pb (<150 mg $kg^{-1}$), or low bioaccessible Pb (<12%) to begin with, and site-specific variability. Sites 2 and 3 began to show the treatment effect after 30 months of treatment, showing increased reduction in monoammonium phosphate and triple superphosphate treatment. Lead speciation analysis conducted on soils collected 1, 12, and 24 months after treatment at Site-1 indicated higher % of pyromorphite-like minerals in all treatments compared to the control. In addition, Pb sorbed to Fe-ferrihydrite was the major Pb species in all treatments. These results supported the continuous reduction of bioaccessible Pb levels at Site-1. Sequential extraction results, clay mineral characterization, PCA, and k-means cluster analyses also supported the above findings. Overall, the study demonstrated that soil amendments are effective in transforming soil Pb into less bioaccessible, pyromorphite-like minerals, even at low levels of Pb contamination from unknown sources in urban areas.

**Acknowledgments**

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# Microbial Induced Carbonate Precipitation (MICP) for Cadmium Contamination Remediation coupled with Life Cycle Carbon Sequestration

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## ABSTRACT

Microbial Induced Carbonate Precipitation (MICP) represents a promising strategy for the remediation of heavy metal pollution coupled with carbon sequestration. This study elucidates the mechanisms and stability of MICP in removing cadmium (Cd), and demonstrates its efficacy in remediating Cd-contaminated paddy rice systems while simultaneously enhancing carbon sequestration, thereby establishing a complete pathway from fundamental research to practical application.

Functional MICP bacterial strains (*Sporosarcina pasteurii* DL-3) were isolated and identified. The removal of Cd via MICP was found to involve five synergistic mechanisms: co-precipitation, precipitation adsorption, cell surface crystallization, extracellular chemical adsorption, and intracellular accumulation. Stability assessments revealed that after MICP treatment, the Cd release rate of Cd-vaterite from solution across a pH range of 2.0–10.0 was 0.286–0.825 ‰. After soil Cd was fixed by vaterite and then eroded by acid rain for 60 days, the fixation rate of exchangeable Cd remained at 51.00%, while the dissolution rate of carbonate-bound Cd was - 0.18%.

The MICP bacterial strain was successfully loaded onto biochar (BC) to form a composite material (BC@DL-3). Pot and field experiments were conducted to evaluate the performance of BC@DL-3 in remediating Cd contamination and promoting carbon sequestration in a farmland–rice system. Compared to the control group, the BC@DL-3 treatment resulted in: no significant yield reduction in pot trials and an increase of 113.55 kg per mu in field trials; Cd content in rice grains decreased by 0.87 mg/kg (pot) and 1.22 mg/kg (field); the fixation rate of exchangeable Cd in soil reached 17.39% (pot) and 52.50% (field); and carbonate-bound Cd increased by 23.20% (pot) and 203.79% (field). These findings clearly indicate that BC@DL-3 can effectively reduce Cd bioavailability in soil and Cd accumulation in rice grains while maintaining or even improving crop yield. A life-cycle carbon budget assessment further demonstrated that while the lime treatment resulted in an emission of -2134.422 kg $CO_2$e per mu, the BC@DL-3 treatment led to carbon sequestration of 623.612 kg $CO_2$e per mu, corresponding to a carbon emission reduction of 129.22%.

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# Reduction of lead bioavailability and phytotoxicity in Pb-slag contaminated soil using soil mixing and compost-modified biochar

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**ABSTRACT**

Food security and human safety are being threatened by heavy metal contamination of agricultural lands. Several physical and biological methods have been employed separately for soil remediation. In this study, effects of combining soil mixing with compost (C) and cow-dung (CD) for reduction and immobilization of Pb in the soil as well as growth, Pb uptake and biochemical responses of maize grown on contaminated soil were investigated. Lead contaminated soil mixed with uncontaminated soil at different ratios to give 0%, 25%, 50%, 75% and 100% levels of contamination were further mixed with C and CD at four different levels (0, 10 20 and 30 t/ha) before planting of maize. Data were collected on maize growth and yield, Photosynthetic Pigments (PP), stress indicators (proline and glycine betaine) contents as well as Pb uptake by maize crop and post-cropping soil Pb concentrations. Pb concentration was reduced by 29-85% in soil mixtures while, C and CD further reduced Pb by 69-77% and 42-66%, respectively. Combined treatments reduced Pb uptake, enhanced maize tolerance and growth as no germination was recorded in 100% Pb contaminated soil. Dry matter accumulation and PP were more in maize crop grown on compost treated soils compared with those grown on soil mixtures only. Proline and glycine betaine contents in maize leaf were reduced in treated plants than untreated plants. Combination of soil mixing with organic amendments could be a better approach for reducing Pb uptake by maize crop and enhanced maize growth on contaminated soil.

***Keywords:*** Heavy metal; Maize; Organic amendment; Osmolytes; Oxidative stress; Restoration

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# Spatial Patterns and Predictive Controls of Heavy Metals in Agricultural Ditch Network Across China

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**ABSTRACT**

Ditch systems work as hierarchical networks that support irrigation in agricultural land. In the event of rainfall, water runs off carrying the sediments which flow out of the upland to the downstream system via the ditch system. In this pathway, every ditch level offers a retention area where the sediments are deposited, and the heavy metals are gradually deposited. As runoff transitioned from cropland to connector (CD), branch (BD), and main ditches (MD), the concentration of metals rose in a stepwise manner, which indicated the progressive retention of metals in the ditch network prior to discharge to rivers. Even though this system controls metal transportation and concentrates metals in cropland, national-scale assessments of these dynamics remain limited. During this study, 166 sediments samples across six agricultural regions in China were analyzed for five metals (Cr, Ni, Cu, Cd, Pb) and the metalloid (As). Sediment concentrations showed clear regional contrasts and modest level-wise shifts along the cropland-ditch hierarchy. Chromium median concentration clustered between 20-27 mg $kg^{-1}$; however, the South-central China cropland showed the highest concentration at about 31 mg $kg^{-1}$. In contrast, the lowest median was recorded in MD of the Southwest region. In the case of the metalloid, the maximum concentration of As was observed in cropland (8.3 mg $kg^{-1}$) relative to CD-MD (6.6-6.9 mg $kg^{-1}$). The concentration of Cd was low, with national median of 0.12-0.17 mg $kg^{-1}$, but the median concentration in CD and BD was high (0.43-0.45 mg $kg^{-1}$) in the Southwest region. North China, East China and South-Central China had the highest concentrations and the greatest variation regionally. The Southwest region was in the middle of concentration range, whereas the Northeast and Northwest were at the bottom of the concentration spectrum. Random Forest models demonstrated relatively low predictive performance, with the highest CV $R^2$ values of Cr and As (0.261 and 0.270, respectively). The most significant predictors of As, Cd, Cr, and Pb concentration were sediment properties, especially silt (%) and sand (%) and soil organic carbon and total phosphate. Conversely, Ni and Cu were primarily driven by chemical properties of ditch system such as salt, TDS, turbidity, and pH. Generally, sediment properties governed the heavier metals, whereas Ni and Cu movement controlled by water chemistry. These patterns revealed that the ditches in agriculture system are a conduit and enrichment and thus strengthen their accumulation along the cropland-to-MD gradient. The regional variabilities also help to point out the areas where the pressures of metal accumulation are the greatest. The combined results underscore the coupled effects of ditch hierarchy and site-specific sediment water conditions shaping heavy-metal distributions across agricultural regions.

**Keywords:** Agricultural systems; Ditches; Heavy metals

# Study on the coupled processes of Cd and Fe transfer in the soil-rice system: a remedial strategy using functional fertilizer

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**ABSTRACT**

At present, cadmium (Cd) pollution in paddy fields is one of the most important agricultural environmental problems that threatens human health via the global food chain. Developing state-of-the-art technologies and products that can simultaneously reduce Cd content while increasing iron (Fe) content in rice grain to ensure food safety and improve human health and nutrition has become a new challenge in the current remediation of Cd-contaminated paddy fields in China. In this study, an independently developed functional fertilizer was selected and a rhizosphere bag-pot experiment was carried out to deeply investigate how Fe redox cycle in the rhizosphere soil affect Cd phytoavailability, and how Fe uptake and translocation within rice plant influence Cd accumulation in the grain during the grain-filling stage. The results showed that upon the functional fertilizer was applied, the contents of HCl extractable Fe(II) and poorly crystalline Fe oxides rose by 35.97% and 21.83%, respectively, and the extremely significant and positive correlation between each other was observed; the organic matter-bound fraction of Fe was transformed to the acid soluble fraction of Fe, whereas the acid soluble fraction of Cd was transformed to the easily reducible manganese and poorly crystalline Fe oxide-bound fraction of Cd; the acid soluble fraction of Fe was not only significantly and negatively correlated with the $CaCl_2$ extractable Cd and extremely significantly and negatively correlated with the acid soluble fraction of Cd, but also extremely significantly and positively correlated with the easily reducible manganese and poorly crystalline Fe oxide-bound fraction of Cd; the contents of Cd and Fe in iron plaque decreased by 32.53% and 31.69%, respectively, and the extremely significant and positive correlation between each other was observed; the content of Cd in rice grain declined by 33.03% while the content of Fe in rice grain increased by 14.93%; the contents of Cd and Fe in root increased by 35.96% and 29.14%, respectively; the $TF_{Cd\text{-}LG}$ dropped by 34.65% and the $TF_{Fe\text{-}LG}$ rose by 23.52%, showing an extremely significant and negative correlation; Pearson correlation analysis and PCA revealed that the content of Cd in rice grain was predominantly governed by the content of Cd in iron plaque and the $TF_{Cd\text{-}LG}$. The functional fertilizer used in this study can simultaneously reduce the content of Cd and elevate the content of Fe in rice grain, offering an immediate pathway for safe rice production and enhancing grain Fe content. These findings provide an important References for the development of some state-of-the-art technologies and products to remediate Cd-contaminated paddy fields in China.

**Acknowledgments**

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# Long-term persistence of immobilizing agents for reducing the phytoavailability of heavy metal(loid)s in contaminated soil

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**ABSTRACT**

Immobilizing agents are widely used to reduce the phytoavailability of heavy metal(loid)s in contaminated agricultural soils; nevertheless, their long-term persistence remains insufficiently understood. This study evaluated the long-term persistence of immobilizing agents in soils contaminated with As, Cd, and Pb. Soils treated with immobilizing agents in 2014 were used for a cultivation experiment in 2017 and then reused for cultivation in 2025 without additional application of immobilizing agents, after which the results from both years were compared. A total of eleven treatments were established: an untreated control; single treatments(lime (L), biochar (B), gypsum (G), compost (CP), soil cover (SC)); and combined treatments(L+CP, L+G, L+SC, L+SMC (spent mushroom compost, SMC), L+CP+SC). The same crop species were grown in both 2017 and 2025, and soil pH, dissolved organic carbon (DOC), and concentrations of heavy metal(loid)s (As, Cd, Pb) in edible plant tissues were analyzed after harvest. Comparison of the two years showed that the lime-containing treatments consistently maintained a reduced phytoavailability of metal(loid)s. This persistence was attributed to the lime effect, which maintained elevated soil pH over time. Therefore, these results suggest that lime-based immobilizing agents provide a practical and long-lasting means to ensure safe crop production by reducing the phytoavailability of heavy metal(loid)s.

# Immobilization of Arsenic and Cadmium in Alkaline Soil Using Combined Red Mud–Phosphogypsum Amendment

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**ABSTRACT**

Arsenic (As) and cadmium (Cd) exhibit contrasting geochemical behaviors in soil, making it difficult to simultaneously immobilize both contaminants using a single amendment. This study evaluated the potential of a combined amendment—red mud (RM), rich in Al/Fe oxides, and phosphogypsum (G), a Ca-rich material capable of moderating soil pH and coagulating dissolved organic carbon (DOC)—to stabilize As and Cd in alkaline soils. Fourteen alkaline soils (pH > 7.5) co-contaminated with As and Cd were collected and packed into 5 L pots. In 2023, RM (1% w/w) and G (1% w/w) were applied to each soil, followed by a one-year incubation period to allow stabilization processes to occur. Rice (*Oryza sativa L.)* was cultivated in 2024, after which soil pH, DOC, and As and Cd concentrations in rice were analyzed to assess RM+G-induced changes relative to untreated controls. Compared with the control, soil pH in the RM+G treatment decreased in all except one soil, from an average of 7.92 to 7.55. DOC concentrations also declined consistently across all soils, from 148.96 mg $kg^{-1}$ to 117.68 mg $kg^{-1}$. As concentrations in rice were reduced in most soils (12 out of 14), decreasing from an average of 0.85 mg $kg^{-1}$ to 0.56 mg $kg^{-1}$. Conversely, Cd concentrations in rice showed only a slight overall decrease (0.57 to 0.51 mg $kg^{-1}$), and notably, 9 out of the 14 soils exhibited higher Cd concentrations in the RM+G treatment than in the control. Overall, the RM+G amendment effectively reduced As uptake by moderating soil pH and DOC levels, whereas Cd showed inconsistent behavior, including increased uptake in many soils. These findings suggest that while RM+G is a promising amendment for As stabilization in alkaline soils, additional mechanistic investigation and follow-up studies are required to clarify Cd mobilization processes and optimize amendment strategies for the simultaneous stabilization of both contaminants.

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# Organic Matter Regulates Soil Cadmium Bioavailability

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**ABSTRACT**

Organic matter is a crucial component of soil, playing a significant role in maintaining soil structure stability and fertility. Farmland management practices aimed at increasing soil organic matter (SOM) content and improving soil fertility are expected to be widely adopted. However, the impact of organic matter input on the chemical speciation and bioavailability of heavy metals in soil remains unclear. Through microcosm simulations, soil incubation experiments, and field remediation studies, we analyzed the influence of different functional components of organic matter and their interactions with minerals on the speciation distribution of cadmium (Cd). The results showed that the composition of soluble organic matter is a key factor regulating Cd mobility, with protein components promoting Cd migration into the solution. After the application of bio-organic fertilizer, the reduction in soil Cd mobility was the primary cause of decreased Cd uptake, and surface complexation modeling further indicated that SOM lowered Cd bioavailability by shifting its speciation from electrostatic adsorption toward organic complexation. Rice Cd accumulation showed a significant negative correlation with extracellular polymeric substances (EPS) content, and the combination of limestone and bio-organic fertilizer significantly increased EPS content and the proportion of EPS-bound Cd. Additionally, organic matter promoted the activation of iron oxides and the formation of stable mineral-organic-Cd complexes through coprecipitation with iron oxides. These findings demonstrate that farmland soil remediation aimed at organic fertilization is a feasible approach.

**Keywords:** Cadmium bioavailability, Soil remediation, Bio-organic fertilizer, Farmland

# Evaluation of Environmentally Important Elements from Glacial Ice-Water and Associated Glacial Sediments

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**ABSTRACT**

Glaciers are land-based ice masses ranging from small cirque glaciers to massive ice sheets like those in Greenland and Antarctica. Glaciers are significant sources of fresh water on planet Earth. The Hindukush–Karakoram–Himalayan (HKH) glaciers provide the water supply to more than half of the human population of the globe, for agricultural activities, biodiversity survival, and ecosystem services. Unfortunately, global warming is causing loss of the mountain cryosphere, with direct impacts on the lives of people living in the vicinity and an indirect impact to those living downstream. In recent years, the loss of glacial ice has been forecasted to cause problems such as sea level rise, changes in water availability, and release of contaminants that reside in the surfaces of glaciers or within them. In this regard, mineralogical sediments play a significant role in the geochemistry of glaciers and element cycling. The ice loss is changing the physicochemical properties of glacier-fed rivers and their aquatic communities. Recent studies have highlighted how glacial microbial diversity varies by region. The richness, abundance, and diversity of microbial populations are greatly affected due to glacier melting and surface exposures. This study analyzed elemental pollutants found in the glaciers of Pakistan and investigated the diverse bacterial communities residing therein. Samples of ice and sediments were collected from the Gilgit, Hunza, and Swat glaciers in northern Pakistan. Nine elements, including co-factors, heavy metals, and nutrients, were assessed using atomic absorption spectrophotometry. The research findings indicate higher concentrations of the elements K, Fe, Cu, and Cr in Hunza glacier ice (Hgi) and Ni, Zn, As, and Cd in Gilgit glacier ice (Ggi). In terms of glacier sediments, Swat (Sgs), Gilgit (Ggs), and Hunza (Hgs) samples showed the highest concentrations of K, Cu, Ni, Zn, As, Pb, Cd, and, respectively, of Fe, and Cr. The amount of Cu and Cr is the same in Swat glacier ice and Swat glacier foot. However, the concentration of some elements (As, K, Pb, Zn) is higher in Swat glacier ice, while the amount of some elements (Cd, Ni) is greater in Swat glacier foot. Furthermore, microbial cultivation techniques revealed diverse bacterial communities inhabiting the sampled glaciers. Phylogenetic analysis of the bacterial isolates, based on 16S rRNA gene sequences, showed high homology (99–100%) with previously reported species. The resultant phylogenetic tree grouped the bacterial isolates, such as *Serratia marcescens*, *Cupriavidus* sp., and *Bacillus cereus*, with closely related species known for their roles in nutrient cycling, environmental resilience, and metal tolerance. These findings highlight the ecological significance and adaptive potential of microbial communities in glacier environments, emphasizing their role in elemental cycling and environmental resilience.

**Keywords:** Glaciers; Microorganisms; Nutrients; Pollutants; Heavy metals

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# Monitoring Cadmium in Soils, Fertilizers, and Baby Leaf Vegetables in Southern Italy: Regulatory and Environmental Insights

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**ABSTRACT**

Cadmium (Cd) contamination in agricultural soils and its transfer to crops is an increasing concern for food safety and public health. In the EU, no harmonized soil threshold values exist, and Member States apply diverse criteria. Although Cd in soil exceeds legal thresholds only in limited areas, its mobility and bioavailability are influenced by soil properties such as pH, texture, carbonate content, and organic matter, which can enhance crop uptake even at low total concentrations. Commission Regulation (EU) 2023/915 sets maximum levels for Cd in food, including leafy and baby leaf vegetables, emphasizing the need to monitor Cd occurrence and its controlling factors.

In March and July 2024, field campaigns in the Sele alluvial plain, southern Italy, sampled soils, baby leaf plants, and fertilizers from organic and conventional horticulture systems. Fields included "problematic" soils where farmers had previously grown baby leaf vegetables exceeding legal Cd limits, and "non-problematic" soils without prior exceedances. Multiple points per field were sampled, and all fertilizers applied during the year were collected to assess potential contributions to Cd inputs.

In the laboratory, soils were air-dried, sieved (<2 mm), and analyzed for physicochemical properties and total and bioavailable metals via acid digestion and ICP-OES/MS. Baby leaf plants were separated into roots and leaves, washed (an aliquot of 50% of each sample), freeze-dried, ground, acid-digested and analysed by ICP-MS for total metals and nutrients. Fertilizers were stored at 4°C, catalogued by type, use, and composition, and analyzed for total elements using mineralization protocols. Data quality was verified with certified References materials, retaining only elements with 80– 120% recovery and ≤20% coefficient of variation.

Problematic soils were clay-rich, while non-problematic soils were sandier. Clay favors metal adsorption and reduces mobility, whereas sandy soils enhance bioavailability. High calcium in all soils may limit solubility, but abundant organic matter in problematic soils can promote Cd complexation and availability. Total toxic metals remained below Italian threshold values, with minor exceedances for Be, Tl, and V due to volcanic soil origins.

In baby leaf vegetables, average Cd was 0.1 mg/kg (organic) and 0.04 mg/kg (conventional); Pb averaged 0.2 mg/kg (organic) and 0.5 mg/kg (conventional). Washing markedly reduced metal content, with non-washed leaves showing Cd and Pb up to 233% higher, reaching EU limits. Fertilizers generally had low Cd and Pb, although an organo-mineral liquid product showed the highest levels, suggesting replacement could reduce crop accumulation.

These results indicate that baby leaf crops, due to short cycles and frequent harvest, may accumulate more metals than full-leaf vegetables. Soils and crops largely comply with regulatory limits, but variability among lots and washed/unwashed differences highlight the need for continued monitoring and further study of metal bioavailability and accumulation.

# Simultaneous immobilization of arsenic and cadmium in paddy soil with co-application of birnessite and lime

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## ABSTRACT

The remediation of arsenic (As) and cadmium (Cd) co-contaminated paddy soils is challenging due to their contrasting biogeochemical behaviors. This study innovatively used the combination of birnessite and lime to mitigate the release of As and Cd in paddy soils. Soil incubation experiments revealed that anaerobic conditions mobilized As, whereas aerobic conditions released Cd. The birnessite-lime treatment effectively addressed both processes, reducing anaerobic porewater As by 29.49%–31.75% and aerobic porewater Cd by 70.76%–99.45% on the last day. Lime application enhanced Cd immobilization by elevating pH, promoting retention of Cd in carbonate precipitation (T2) and Fe/Mn oxide phases (T3). However, lime application stimulated Fe-reducing bacteria, decreasing Fe oxide-bound As (F3+F4) but increasing specifically adsorbed As (F2), thus rendering the net effect on As dissolution dependent on the balance of these processes. Birnessite counteracted the lime's negative aspect on F3+F4 via inhibiting anaerobic reductive dissolution of Fe oxides. Pot experiments confirmed that the combined treatment (1‰ birnessite and 0.5% lime) reduced As and Cd uptake in rice seedlings by 13.26%–37.57% and 43.76%–70.89%, respectively. Notably, excessive lime (1‰ birnessite_1% lime) elevated As bioavailability, highlighting the need for soil-specific dosing. This redox-adsorption coupled strategy offers a cost-effective solution for As-Cd co-contaminated paddies and similar waterlogged ecosystems.

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# Mechanisms and Risk Control of Chromium Uptake in Rice: The Pivotal Role of Colloidal Formation

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**ABSTRACT**

Conventional assessments of heavy metal contamination in paddy systems focus predominantly on dissolved metal ions, largely neglecting colloidal forms—despite their prevalence in flooded soils. Trivalent chromium (Cr(III)), in particular, has been considered low-risk due to its presumed low solubility and precipitation tendency, leading to its systematic underestimation in environmental risk evaluations. Here, we show that under typical paddy redox fluctuations, Cr(III) readily forms stable colloids with markedly increased mobility and interfacial activity, thereby enhancing its bioavailability and potential for food-chain transfer.

We compared the uptake, translocation and subcellular distribution of soluble versus colloidal Cr using rice as a model system. In aqueous environments, inorganic chromium rapidly transformed into colloidal aggregates that strongly adsorbed to root surfaces. These aggregates acted as interfacial reservoirs, substantially promoting chromium accumulation in both roots and shoots. In contrast, strongly chelated soluble Cr remained stable in solution, showed limited interaction with roots, and was poorly taken up and translocated. Further size-fractionation experiments revealed that smaller Cr colloids were internalized via active cellular pathways, whereas larger colloids or those with a strong adsorption capacity were predominantly sequestered in cell walls and rhizosphere microenvironments.

Our findings demonstrate that colloidal transformation fundamentally reshapes the environmental behavior and risk profile of heavy metals in flooded soils. Recognizing colloidal species as dynamic and bioavailable pollutant forms is therefore essential for accurate exposure assessment, improved risk management, and effective mitigation of heavy metal contamination in rice-producing ecosystems.

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# Assessing Heavy Metal Pollution Levels and Associated Ecological Risks in Peatland Sediments of the Mekong Delta, Viet Nam

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**ABSTRACT**

Heavy metal (HM) contamination in peatland sediments is an emerging concern, yet evidence for Vietnamese peatlands remains limited. The study evaluated HM levels and ecological risks in three peatland districts of Long An Province, Viet Nam (Tan Thanh, Thanh Hoa and Duc Hue). Thirty surface sediment samples (5–15 cm; n=10 per district) were analyzed for Mn, Ni, Pb, Cd, Cu and Zn, together with pH, salinity, electrical conductivity (EC), total organic carbon (TOC) and texture. Pollution was interpreted using sediment quality guidelines and indices: contamination factor (CF), modified degree of contamination (mCd) and potential ecological risk index (RI). Source apportionment applied positive matrix factorization (PMF); relationships were explored using Spearman correlation and Bayesian network analysis. Cu and Ni were highest in Tan Thanh and reached 2–3 times the threshold effects level (TEL) and effects range-low (ERL) guidelines. CF indicated moderate-to-considerable degree pollution for Ni (CF=1.3 in Thanh Hoa; 3.2 in Tan Thanh) and moderate degree pollution for Cu in both areas (CF=1.3–2.4). mCd ranked contamination as Tan Thanh (1.3) > Thanh Hoa (0.7) > Duc Hue (0.4). RI suggested overall low ecological risk (mean RI=35.6). PMF identified six factors; the dominant factor contributed 49.2% and was strongly associated with Cd, Ni and Zn, consistent with fertilizer and pesticide inputs. HM concentrations were positively associated with pH, TOC and fine fractions (clay+silt). These results provide baseline evidence for HM status in Mekong Delta peatlands and support targeted management to reduce metal loading.

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# Phytoremediation of Multi-Metal Contaminated Mine Soils: Native Species Screening and Chelate-Assisted Phytoextraction

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**ABSTRACT**

Mining-impacted soils in Thai Nguyen, Viet Nam are contaminated by heavy metals (HMs). The study assessed HMs occurrence (As, Cd, Cu, Pb, Zn) and evaluated the accumulation of HMs in native plants and factors impact them in contaminated mining sites in Vietnam: Ha Thuong lead–zinc (HT), Trai Cau iron (TC) and Hich Village lead–zinc (LH). Native species were screened for remediation potential, focusing on Erianthus arundinaceus (EA) and Phragmites australis (PA). Chelate-assisted phytoextraction was evaluated using ryegrass (Lolium multiflorum Lam.) amended with ethylenediaminetetraacetic acid (EDTA; synthetic), ethylenediaminedisuccinic acid (EDDS; biodegradable) and nitrilotriacetic acid (NTA; biodegradable), applied as a single dose (1:1) or split/sequential dose (0.5:1 + 0.5:1). Controls displayed normal growth without visible metal-toxicity symptoms. Across sites, chelates significantly increased metal concentrations in ryegrass shoots versus controls. Split dosing outperformed single dosing for As, Pb and Zn in LH soil; the EDTA split dose delivered the highest increases in Zn (6.15-fold), Pb (69.5-fold) and Cu (1.49-fold), while the NTA split dose maximized As (18.47-fold). In HT soil, single-dose chelates more effectively enhanced Zn in shoots than split dosing, highlighting site-specific response. Field observations indicated EA tolerated multi-metal stress and produced high biomass, supporting phytostabilization. EA has the potential for phytostabilisation of Cd-contaminated sites. Overall, combining tolerant native plants for stabilization with carefully managed (preferably biodegradable) chelate strategies for extraction offers a practical remediation pathway for mine-affected soils, provided leaching risks are controlled. These responses indicate that chelate type and dosing should be tailored to local soil conditions and target metals to balance removal efficiency and environmental safety.

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# Speciation of Heavy Metals in Soil and Their Influencing Factors in a Tailings-Affected Area of Eastern Inner Mongolia

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**ABSTRACT**

The speciation of heavy metals in soil determines their mobility and toxicity, making the analysis of their speciation crucial for understanding their environmental migration behavior and conducting risk assessments. This study focuses on soil surrounding a lead-zinc tailings area in eastern Inner Mongolia, where the total concentrations and speciation distributions of four heavy metals—Zn, Pb, As, and Cu—were determined. The pollution level was assessed using the single-factor index and geo-accumulation index, while an improved Tessier sequential extraction technique was employed to analyze their speciation characteristics, thereby evaluating the ecological risks and migration potential of these heavy metals. The results showed that the average concentrations of heavy metals in the soil followed the order Zn > Pb > As > Cu, which were 31.39, 23.60, 16.12, and 12.50 times the background values, respectively. The pollution degree of heavy metals was ranked as As > Zn > Pb > Cu, with arsenic being the most prominent pollutant. Speciation analysis indicated that the four heavy metals primarily existed in the residual and iron-manganese oxide-bound forms, exhibiting relatively high environmental stability. Additionally, carbonate-bound copper, sulfide- and carbonate-bound zinc, organic-bound arsenic, and carbonate-bound lead also accounted for certain proportions. Risk assessment based on bioavailable forms revealed that the overall ecological risk of heavy metals in the soil ranged from low to moderate, with zinc having the highest bioavailability and arsenic the lowest. In summary, the soil in this area is contaminated by multiple heavy metals, with arsenic being the primary pollutant. Although heavy metals predominantly exist in less active forms, they still pose potential release risks.

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# Mechanism of Auxin Regulation on Cadmium Uptake in Roots of Different Cadmium-Accumulating Rice Lines

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**ABSTRACT**

ABSTRACT:Cadmium (Cd) is a heavy metal element with high bioavailability. When rice is cultivated in Cd-contaminated soil, it often leads to excessive Cd accumulation in grains, posing a serious threat to food security and human health. Therefore, investigating the mechanisms to reduce Cd accumulation in rice is of significant importance. Auxin (IAA), a key endogenous factor regulating plant growth and stress responses, has been reported to influence Cd uptake and accumulation in plants, though its regulatory mechanisms remain unclear. The study indicates that: (1) Under Cd stress, there are differences in IAA response between the two rice lines, with the IAA concentration in the roots of the high-accumulation rice line Lu527-8 being significantly higher than that of the common rice line Lu527-4. Combined with transcriptome analysis, it was found that the expression patterns of the primary IAA response factor auxin up-regulated small RNA (OsSAUR) and the key rate-limiting enzyme gene in the phenylpropanoid biosynthesis process, namely phenylalanine ammonia-lyase gene (OsPAL), were consistent, suggesting that IAA may regulate lignin synthesis through OsPAL, thereby affecting the development of the apoplastic barrier; (2) Exogenous IAA reduced Cd accumulation in rice by limiting root Cd uptake, with Cd accumulation decreasing by 27.72% and 8.20% in Lu527-8 and Lu527-4, respectively. IAA limited apoplastic and symplastic Cd uptake in the roots of Lu527-8 by enhancing the development of the apoplastic barrier and reducing the expression of Cd transporters. However, for Lu527-4, IAA only limited the symplastic Cd uptake process in roots by decreasing the expression of Cd transporters. This is the main reason for the significant difference in Cd accumulation reduction between the two rice lines. In summary, under Cd stress conditions, exogenous IAA application can reduce Cd accumulation in the roots of the high-Cd-accumulating rice line Lu527-8 by simultaneously regulating both apoplastic and symplastic pathways, whereas the common rice line Lu527-4 primarily relies on the regulation of the symplastic pathway.

**Key Words:** auxin; Cd accumulation; rice; apoplastic barrier; transporter

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# Regulatory Effects of Nitrogen and Acetate on Arsenic Adsorption by Bentonite in an Anaerobic System

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**ABSTRACT**

Arsenic contamination has become a global environmental issue, posing significant threats to both ecosystems and human health. Statistics indicate that over 200 million people worldwide are at risk of arsenic exposure. To address this challenge, various remediation technologies have been developed and applied. Among them, adsorption has been recognized as one of the most promising techniques due to its high efficiency, cost-effectiveness, and operational simplicity. Bentonite, a natural clay mineral, has demonstrated great potential for arsenic remediation. However, research on the influence of nitrogen compounds on arsenic adsorption by bentonite in agricultural and aquatic environments remains limited. In this study, batch experiments were conducted under anaerobic reducing conditions to systematically investigate the effects of exogenous nitrogen addition on arsenic adsorption by bentonite. Furthermore, the regulatory role of low-molecular-weight organic acids, particularly acetate, in this system was explored. The results revealed that: (1) the arsenic adsorption efficiency of bentonite exhibited a significant negative correlation with the amount of exogenous nitrogen added, while the chemical form of nitrogen (nitrate or ammonium) had no significant effect; (2) acetate exerted a dual effect on arsenic adsorption: moderate acetate concentrations (0.2-0.5 g) enhanced arsenic adsorption, whereas excessive acetate (>0.8 g) significantly inhibited the adsorption capacity of bentonite. These findings provide valuable theoretical insights into the application of bentonite for arsenic remediation in anaerobic reducing environments and highlight the necessity of optimizing exogenous nitrogen and organic acid concentrations in practical applications.

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# Metallomes in Soil-Crop Systems: Integrating Nutrition and Food Safety

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**ABSTRACT**

Metals and metalloids (hereafter termed as metals) are ubiquitous in agricultural ecosystem. Food crops can take up both toxic and nutritional metals from soils, resulting in their transfer through food chain and subsequent dietary intake by humans. The lack of essential metals and/or the excess of toxic metals in crops and diets can cause adverse health outcomes including severe chronic diseases. Thus, the entire composition of metals (i.e., metallomes) in crops should be studied and managed to enhance nutrition and food safety. Here we hypothesize that crop metallomes can be optimized by agricultural practices such as plant breeding, soil water and nutrient management, cropping practices, etc. We have studied how soil water conditions, plant growth stages, and soil amendment applications could influence the metallomes of carrot (*Daucus carota* subsp. *Sativus*) and wheat (*Triticum aestivum*) grown in sandy soil under laboratory and greenhouse conditions. Our results showed that metallomes in carrots and wheat were primarily controlled by plant growth stages, with limited effect from soil water conditions. Interestingly, wheat kernels showed different metallomes among varying soil water conditions. For carrot seedlings the correlated metallomes in carrot roots did not significantly change with soil amendments, whereas the non-correlated metallomes could be influenced by soil amendments. We then explored the metallomes of carrots grown to maturity in greenhouse with single or combined soil amendments (e.g., biochar). We are further studying crop metallomes under field conditions and explore environmental and biological controls on crop metallomes using multi-omics approaches. It could be possible to optimize crop metallomes through agricultural practices for enhanced nutrition and food safety, thus improving public health.

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# α-ketoglutarate mitigates Cd accumulation and enhances Cd tolerance in rice

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**ABSTRACT**

Rice is a major crop in China with a strong tendency to accumulate cadmium (Cd), posing serious risks to grain safety. α-Ketoglutarate (AKG), a key tricarboxylic acid cycle intermediate, has known roles in abiotic stress responses, but its effects on Cd tolerance and accumulation in rice remain unexplored. Exogenous AKG (50 μmol/L) was applied to investigate the mechanism regulating Cd tolerance and accumulation under both hydroponic and soil conditions. Under hydroponic experiments, exogenous AKG significantly reduced Cd translocation by 56.8–63.9%, and decreased shoot Cd accumulation by 54.9–60.6%. It alleviated photoinhibition and oxidative damage by enhancing photosynthesis and antioxidant activities while lowering $H_2O_2$ and MDA. Mechanistically, multi-omics analyses showed AKG confers Cd tolerance and Cd restriction concentration-dependently. Under moderate Cd stress, AKG predominantly enhances the ascorbate-glutathione cycle and flavonoid biosynthesis for antioxidative defense, while upregulating *OsHMA3* and reinforcing the endodermal barrier to restrict Cd transport. Under severe Cd stress, AKG shifts to activating melatonin biosynthesis and further suppressing transporters like *OsIRT1*. Additionally, AKG reduced grain Cd by 40.7% and increased yield by 31.6% under soil conditions. These results demonstrated the effective role of AKG in integrated Cd mitigation and provide a novel strategy for safe rice production in Cd-contaminated soils.

# Accumulation characteristics and risk prediction of Cu and Zn contents in typical facility soils in China

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**ABSTRACT**

Excessive accumulation of trace elements in the protected cultivation soil has become an important factor for the degradation of soil quality. In particular, both copper (Cu) and zinc (Zn) are micronutrient elements required for plant growth and heavy metal in the soil environment. It is highly demanding to consider the Cu, Zn cumulative risks. Therefore, this study aims to investigate the accumulation characteristics and risk prediction of Cu, Zn content in the protected cultivation soil. A total of 131 soil samples were also collected using 5-point sampling in the typical regions of 16 cities in 7 provinces and 1 autonomous region (including Liaoning, Hebei, Shandong, Henan, Shaanxi, Jiangsu, Yunnan, and Ningxia) in China. The cumulative status and risk characteristics of Cu and Zn were systematically analyzed using the total and available content of the soil. The relationship between the accumulation of available Cu, Zn, and the planting years was fitted to predict the risk of Cu and Zn accumulation exceeding the limit value. The results showed that: 1) The total Cu and Zn exhibited an accumulative characteristic in the protected cultivation soil, except that Cu presented a slight decrease in Jiangsu. The effective state content of Cu and Zn (except that Zn at a relatively rich level both in Shaanxi and Jiangsu) reached an extremely rich level, where there was no state below the critical value. Noted that the soil background values in each province were compared with the abundance and deficiency indexes of soil available trace elements in the agricultural system. 2) The total amount of Cu and Zn in the soil exceeded the standard by 16.03% and 4.58%, respectively, compared with the screening value of farmland soil. The average exceeding limit rate reached 16.92%, while Liaoning, Henan and Yunnan were observed the most serious up to 33.33%, 62.50%, and 32.00%, respectively, compared with the risk limits of soil available Cu and Zn. 3) The risk assessment showed that the overall performance of protected cultivation soil was safe using the effective state. The samples from Liaoning, Henan, and Yunnan reached the level of lightly, lightly pollution, and warning value level, respectively. The cumulative risks of elemental Cu were more serious than Zn element. 4) There was a significant positive correlation between the accumulations of soil available Cu and Zn with the corresponding planting years ($P<0.05$). The continuous replanting for 6.7, 20.5, and 19.3 years led to the accumulation of available Cu in soils with acidic, neutral, and alkaline limit values of characteristics reach risk, respectively, under the current protected cultivated conditions. At the same time, the continuous replanting for 32.5, 67.9, 91.9 years led to the accumulation of available Zn in the soils with acidic, neutral, and alkaline limit values of characteristic reach risk. The bioavailable state of trace element was used to evaluate the exceeding limit rate of Cu and Zn, while the cumulative risk in the protected cultivated soil, in order to achieve the safe utilization via transforming the excess bioavailable to low state, (such as residue, oxidizable, and reducible state). Therefore, there was a high risk in the accumulations of Cu and Zn in the protected cultivated soil in the practice, where the trends were ever increasing year by year. Consequently, it is necessary to take reasonable and safe measures (including restoration technology and selection of agricultural materials), further to ensure the healthy and sustainable development of protected cultivated agriculture. The extension limit is 3000 characters with spaces in total, this including Acknowledgments and References if any.

**Acknowledgments**

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# Bioavailability and Mobilization of Colloidal Cd in Alkaline Soils of Wheat Field

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## ABSTRACT

High soil pH is generally known to inhibit cadmium (Cd) bioavailability, yet wheat grains from alkaline wheat-growing regions in China often exceed Cd safety thresholds. This paradox may be partly explained by the overlooked contribution of colloidal Cd to wheat Cd uptake. Nevertheless, research on colloidal Cd in alkaline wheat soils remains limited, particularly regarding two key issues: First, differences in mineral composition among soil types may alter the binding forms and stability of colloidal Cd, thereby influencing its bioavailability. Second, freeze–thaw cycles (FTCs), which are common in farmlands of northern China, may promote the release of colloidal Cd from aggregates of different sizes. Therefore, the objectives of this study were to 1) clarify the effect of soil type (characterized by differences in mineral composition) on the bioavailability of colloidal Cd in alkaline soils; 2) elucidate the mechanisms underlying the mobilization and release of colloidal Cd from aggregates with different particle sizes during FTCs. In this study, we collected colloidal Cd from Cd-contaminated soils and conducted hydroponic experiments to verify the bioavailability of soil colloidal Cd and their influencing factors. Furthermore, we employed stable Cd isotope tracing technology to quantitatively analyze the release characteristics of colloidal Cd in soil aggregates of different particle sizes during FTCs.

Results shows that over 90% of Cd in soil solution exists as colloids. Colloidal Cd content was weakly related to total soil Cd but showed significant positive correlations with soil pH and colloidal Al content. AF4 analyses revealed that Cd primarily forms mineral–organic colloidal complexes with aluminosilicates, with particle sizes ranging from 100 nm to 1 μm. Hydroponic experiments confirmed that colloidal Cd is bioavailable to wheat, indicating that colloids are an important Cd source rather than inert carriers. In addition, soil FTCs significantly increase the content of colloidal Cd in soil. Isotope tracing results indicated that macroaggregates are the primary source of colloidal Cd during FTCs (contribution rate: 49.6%–65.1%). The fine fraction contributed only marginally (< 5%), despite its higher Cd concentration. SEM–μCT–DSC analyses further showed that macroaggregates, characterized by larger pores and higher free water content, readily disaggregated and released colloidal Cd during FTCs, while fine particles resisted disaggregation and acted as sinks for Cd colloids. Overall, our findings demonstrate that colloidal Cd are the dominant form of Cd in alkaline soils and can significantly contribute to Cd uptake by wheat. Furthermore, FTCs in alkaline soils intensifies the release of colloidal Cd, and this suite of processes may further facilitate Cd accumulation in wheat grown in alkaline soils.

**Acknowledgments**

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# Distinct assembly processes and ecological strategies of bacterial and fungal communities during the aging of Cd and As in soils: Fungi play a predominant role in microbial resistance

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**ABSTRACT**

The contamination of agricultural soils with cadmium (Cd), arsenic (As), and their combined pollution has become increasingly severe in China. This study systematically investigated the response characteristics and ecological mechanisms of soil microbial communities during the aging process of Cd, As, and their combined pollution through soil microcosm incubation experiments combined with amplicon and metagenomic sequencing technologies. Results revealed that Cd/As aging significantly altered microbial community structure and function. During aging, bacterial α-diversity exhibited an initial decrease followed by an increase, while fungi showed the opposite trend. High-concentration Cd-As co-contamination demonstrated synergistic toxicity that persistently suppressed microbial diversity. Medium- and low-concentration Cd/As treatments and their combinations significantly induced the enrichment of heavy metal-tolerant taxa in later aging stages, including increased relative abundance of genus *VBCG01* (bacteria) from 1.88% to 2.03%-3.45%, and *Mortierella* (fungi) from 16.82% to 17.01%-20.28%. Co-contamination enhanced the complexity of bacterial-fungal-cross-domain ecological networks, indicating its role in driving microbial functional differentiation and dynamic equilibrium of resource competition while enhancing system resilience. Community assembly analysis showed deterministic processes in bacterial communities initially increased then decreased with aging time, whereas fungal communities exhibited the reverse pattern, reflecting their distinct ecological adaptation strategies under heavy metal stress. Both microbial kingdoms initially responded to environmental factors through nutrient salts/ion exchange before shifting to organic matter/K+ metabolism coordination in later stages. Based on community mean tolerance breadth (CMTB) and response asynchrony (CMRA) analyses, co-contamination groups showed the highest resistance potential in late aging stages, while Cd/As single pollution demonstrated more persistent negative impacts. PLS-PM analysis revealed that aging processes modified bioavailable heavy metal fractions and soil physicochemical properties, thereby regulating microbial community characteristics and resistance potential, with fungi contributing more significantly to resistance. These findings provide theoretical foundations and data support for ecological risk assessment and microbe-driven remediation strategies in contaminated farmland ecosystems.

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# Source-risk-driver analysis of heavy metal pollution in karst soils: An integrated assessment in eastern Yunnan, China

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**ABSTRACT**

The fragile karst ecosystems in eastern Yunnan are confronting severe challenges from soil metallic pollutants (SMPs). This study innovatively constructs a "Source-Risk-Driver" (SRD) framework to systematically unravel the dynamics of SMP contamination through three dimensions: source identification, risk quantification, and driver prioritization. By integrating pollution indices, positive matrix factorization (PMF), and Geodetector models, a multidimensional analysis was conducted on six SMPs in the region. Key findings include: (1) SMPs originate from the interplay between karst geological processes (e.g., carbonate weathering) and anthropogenic activities (agricultural inputs, industrial emissions, and transportation). PMF source apportionment revealed that 17.9% of the pollution load stems from agro-natural synergistic sources. (2) The Natural-Agricultural Composite Source dominated ecological risks (contribution rate: 77.17%), primarily driven by cadmium. (3) Geodetector quantification identified SMP concentration gradients, socioeconomic pressures (GDP and population density), and climatic stressors (temperature and evapotranspiration) as the primary drivers of risk spatial differentiation. The SRD framework elucidates, for the first time, the cascading linkages from pollution sources to risk manifestation and their socio-environmental drivers in karst regions. This provides a theoretical basis for implementing sourceoriented control strategies (e.g., prioritizing agro-natural synergistic source management) and establishing crosssectoral governance frameworks (e.g., reconciling mineral exploitation with ecological conservation policies).

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# Study on the Effects of Different Types of Humic Acids and Iron-Manganese Oxides on the Speciation of Heavy Metals in Soil

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**ABSTRACT**

The chemical forms of heavy metals in soil determine their mobility and toxicity, making the analysis of these forms crucial for understanding their environmental transport behavior and conducting risk assessments. This study focused on soils surrounding a lead-zinc tailings area in eastern Inner Mongolia, measuring the total concentrations and speciation distribution of four heavy metals: zinc, lead, arsenic, and copper. Pollution levels were evaluated using the single factor index and the geo-accumulation index, while an improved Tessier sequential extraction method was employed to analyze their speciation characteristics. The results indicated that the pollution degree of heavy metals in the soil followed the order: As > Zn > Pb > Cu. These four heavy metals primarily existed in residual and iron-manganese oxide-bound forms, exhibiting high environmental stability. The speciation of metals can be modified by the addition of various types of humic acids and different concentrations of iron-manganese oxides. Four types of humic acids were utilized: fulvic acid (FA), humic acid (HA), humin, and total humic acids. The addition of total humic acids resulted in an increase in the bioavailable forms of zinc (Zn) and arsenic (As), while the bioavailability of lead (Pb) and copper (Cu) decreased. Conversely, the introduction of the other three types of humic acids led to a decrease in the bioavailability of Zn, Pb, and Cu, whereas the bioavailability of As increased, with the bioavailable forms diminishing as the concentration of humic acids increased. Over time, the bioavailable forms of Pb and Cu in the soil increased following the addition of humin and humic acid, while the bioavailable form of As in the soil increased after the addition of fulvic acid and humin. Upon the addition of varying concentrations of iron-manganese oxides, the predominant forms of As were found to be residual and primarily sulfide-bound states. Zn predominantly existed in iron-manganese oxide-bound and residual states, while Pb primarily occurred in iron-manganese oxide-bound, primary sulfide-bound, and residual states. Cu was mainly found in organic-bound, primary sulfide-bound, and residual states. Throughout the aging period, the bioavailable fractions of all four heavy metals exhibited a decreasing trend. In conclusion, the soil in this area is contaminated by multiple heavy metals, with As identified as the primary pollutant. Although these heavy metals primarily exist in low-activity forms, there remains a potential risk for their release.

# Colloidal Cd Mobilization During Reductive Dissolution of Cd-Birnessite by Organic Matter: Role of pH-Dependent Mineral Transformation and Organic Fractionation

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**ABSTRACT**

Cadmium (Cd) immobilized on manganese oxides ($MnO_x$) in soils can undergo remobilization through reductive dissolution by natural organic matter (OM). However, the dominant Cd species released in this process remain incompletely understood, particularly under different pH conditions. Herein, we investigated dynamic Cd speciation during anaerobic reduction of Cd-bearing birnessite by Suwannee River Fulvic Acid (SRFA), revealing a progressive dominance of colloidal Cd throughout the experiment. This trend amplified at higher pH, as evidenced by its ultimate contribution of 36.6%, 57.8%, and 77.1% to total dissolved Cd at pH 4.5, 6.0, and 8.0, respectively. Moreover, two distinct colloidal Cd fractions were identified by asymmetrical flow field-flow fractionation, extend X-ray absorption fine structure, and Fourier transform ion cyclotron resonance mass spectrometry. The first fraction (1 kDa–50 nm) carried 27.7–45.6% dissolved Cd via complexation with SRFA derivatives, exhibiting lower oxidation state, higher susceptibility to reoxidation, and increased Cd release risk. The second fraction (200–450 nm) carried 8.9–31.6% dissolved Cd and evolved from organic aggregates into $MnO_x$-OM colloids. These composite colloids could enhance colloidal Cd stability and potential mobility, especially under pH 6.0 and 8.0, due to stable crystalline manganite/hausmannite formation and enriched oxidized organic matter. We highlight that the released colloidal Cd during $MnO_x$ reductive dissolution under varying pH could exhibit variable mobility, reactivity, and environmental risk.

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# Quantitative Analysis of Heavy Metal Pollution Sources, Influencing Factors, and Delineation of Pollution Risk Areas in Mining Area Soil: A Combined machine learning and Application of Receptor Models

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**ABSTRACT**

To examine the characteristics of heavy metal contamination in soils, pollution sources, and the risk to agricultural product quality in typical heavy metal mining areas, a study was conducted in a city in Guizhou Province with a history of concentrated lead-zinc mining activities. A total of 1,500 surface soil samples were collected to measure the contents of eight heavy metals: Cd, Pb, Cr, Cu, Ni, Zn, Hg, and As. The study combined the Random Forest (RF) model and Positive Matrix Factorization (PMF) receptor model for comprehensive source analysis, and used the Geo-accumulation Index (Igeo) and Potential Ecological Risk Index (RI) to assess pollution levels and ecological risks, while also investigating the enrichment effect of heavy metals in maize. The results showed that the average content of all eight heavy metals exceeded the background values of soils in Guizhou, with Cd reaching severe pollution levels (Igeo = 1.79). The sources of soil heavy metal pollution were primarily natural and anthropogenic, contributing 27.38% and 72.62% respectively. Among anthropogenic sources, transportation, atmospheric deposition, crop-focused agricultural activities, and metal mining-based industrial activities contributed 12.05%, 15.2%, 34.62%, and 10.75% of heavy metals, respectively. The Random Forest (RF) model evaluation indicated a complex interaction between factors affecting heavy metal accumulation, with pesticide and fertilizer usage playing significant roles. The RI was 441.84, classified as Level III, indicating medium to high risk, with potential risk from Cd needing special attention. Maize showed significant differences in bioaccumulation capacity for different heavy metals: the Cd enrichment factor was 0.04, demonstrating strong accumulation; Cr, Hg, and As enrichment factors ranged from 0.008 to 0.03, showing moderate accumulation; while Pb had the lowest enrichment factor of 0.002. These findings provide a scientific basis for precise prevention and control of soil heavy metal pollution in the region.

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# Land use shapes air-surface Hg0 exchange in karst areas

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**ABSTRACT**

This study investigates how land use types mediate air-surface $Hg^0$ exchange in three karst catchments including Shawan, Chenqi, and Huilong in Southwest China. Using dynamic flux chamber (DFC) and Hg isotope analysis. This study demonstrates that the dominant factor regulating the direction and magnitude of $Hg^0$ fluxes is land cover, and this finding holds true across regions with varying soil Hg backgrounds. In Shawan, annual $Hg^0$ emissions were highest from bare land at 4.55 ng $m^{-2}$ $h^{-1}$, while grassland functioned as a net sink with an uptake flux of -1.82 ng·$m^{-2}$ $h^{-1}$. In Chenqi, moderate emissions were observed from dry agriculture land at 5.67 ng·$m^{-2}$ $h^{-1}$, while forest and grassland acted as net sinks during autumn. In Huilong, dry agriculture land emissions as high as 267.2 ng·$m^{-2}$ $h^{-1}$ were observed, which was approximately tenfold higher than that from forest areas. Mercury emissions peaked in summer across all sites due to high temperature and strong solar radiation. Mercury isotope analysis showed significant kinetic fractionation, with $\delta^{202}Hg$ values as low as -2.75‰ in emissions from low-vegetation areas, indicating preferential release of lighter Hg isotopes during volatilization. Soil organic carbon (SOC) emerged as a key mediating factor, showing a significant positive correlation with Hg concentration but a negative correlation with $Hg^0$ flux, underscoring its role in inhibiting Hg re-emission. This study demonstrates that maintaining well-vegetated landscapes can reduce Hg emissions by over 90% compared to disturbed surfaces. These findings highlight the critical importance of land use specific management, such as preserving forest cover and regulating agricultural practices for mitigating Hg dispersion and strengthening ecosystem sink capacity in vulnerable karst regions, providing a scientific basis for targeted Hg risk control and ecological sustainability strategies.

**Keywords:** $Hg^0$ flux magnitude; land use effect; Hg isotopes; air-surface exchange; karst area

Highlight:

(1) Vegetation cover reduces $Hg^0$ emissions by over 90% compared to bare or disturbed land, transforming landscapes from net sources to sinks.

(2) Mercury isotopes confirm that low-vegetation areas favor kinetic release of light Hg, while vegetation shifts reduction pathways and suppresses volatilization.

(3) Soil organic carbon enhances Hg retention and strongly inhibits re-emission, highlighting its key role in sustaining the sink capacity of vegetated ecosystems.

**Acknowledgments:** This work was supported by the National Natural Science Foundation of China (42107497).

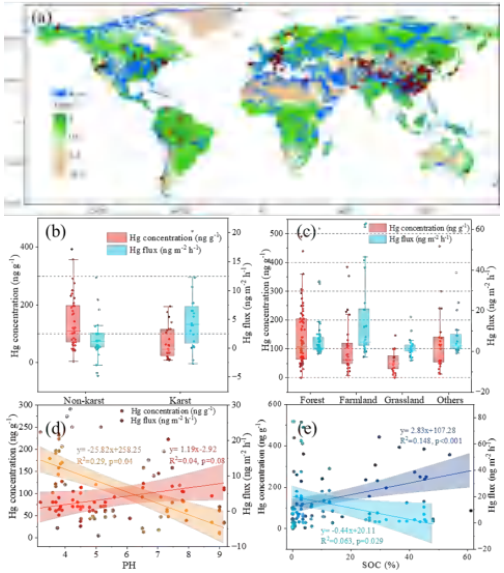



Figure 1. Global patterns of air-surface Hg0 exchange across land uses and karst versus non-karst ecosystems.

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# Machine learning-supported determination for site-specific natural background values of soil heavy metals

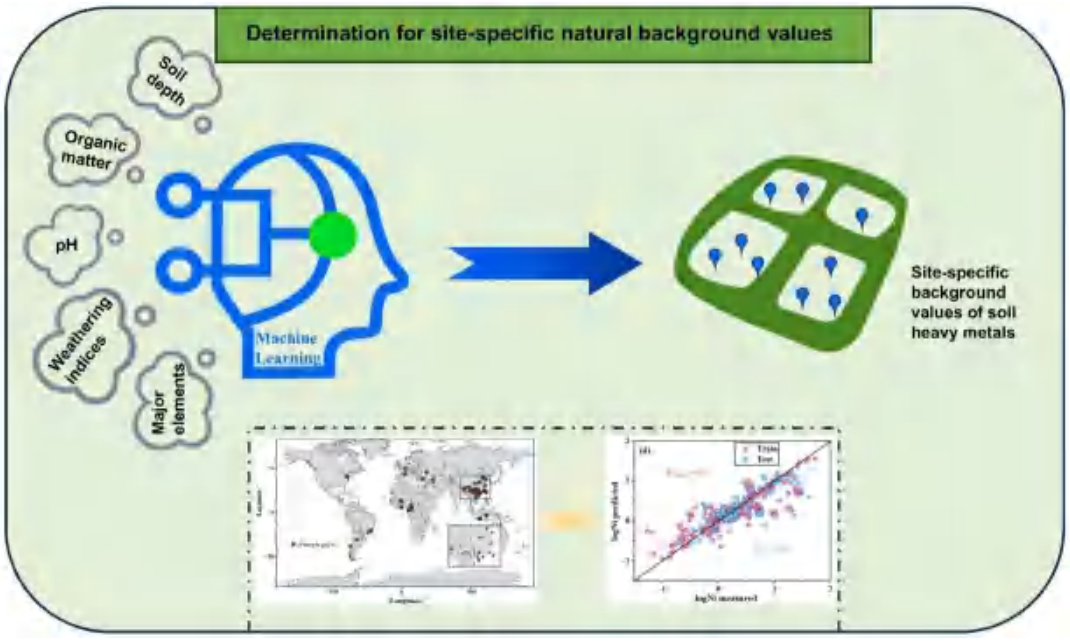
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**ABSTRACT**

Heavy metal natural background values play a crucial role in distinguishing anthropogenic sources from natural sources to assess human impacts in polluted areas, thereby accurately formulating environmental policies. However, due to limitations imposed by human activities, research methods, and regional constraints, the determination of heavy metal background values, particularly on site or profile scale, is often challenging, highlighting the urgent need for new methodologies. To establish a comprehensive dataset containing heavy metal concentrations and soil properties, the study systematically collected and screened 82 soil profiles from areas minimally affected by human activities, resulting in a total of 2185 data sets. Using soil depth, pH, organic matter, weathering indices (SAF, BA), $Fe_2O_3$, MgO, $Na_2O$, CaO, and $K_2O$ as model input variables, the predictive performance for site-specific background levels of Cd, Cr, Cu, Ni, Pb, and Zn was compared across four advanced machine learning models (RF (random forest), XGBoost (extreme gradient boosting), ANN (artificial neural network), SVR (support vector regression)). The results indicated that the optimal model for predicting background values of Cd, Cr, and Ni was XGBoost (MAE = 0.14 – 0.17; MSE = 0.04 – 0.06; $R^2$ = 0.82 – 0.87), while RF was used for Cu, Pb, and Zn (MAE = 0.01 – 0.18; MSE = 0.02 – 0.06; $R^2$= 0.89 – 0.95). Importance assessments using RF and SHAP revealed that pH is a key controlling factor for Cd and Ni, $Fe_2O_3$ significantly impacts Cr, Cu, and Zn background levels, and $K_2O$ is the main controlling factor for Pb. The machine learning models developed can effectively predict the background levels of these six heavy metals based on major elemental and soil physicochemical properties, particularly achieving accurate predictions for Cu and Zn using just two input variables. This machine learning prediction framework is based on major elemental compositions and the physical/chemical properties of soil, enables precise and cost-effective point-to-point environmental assessments, thereby offering significant potential for practical applications.



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# Two-stage heavy metal enrichment during carbonate rock weathering-pedogenesis: Micro-scale evidence from soil-rock interface

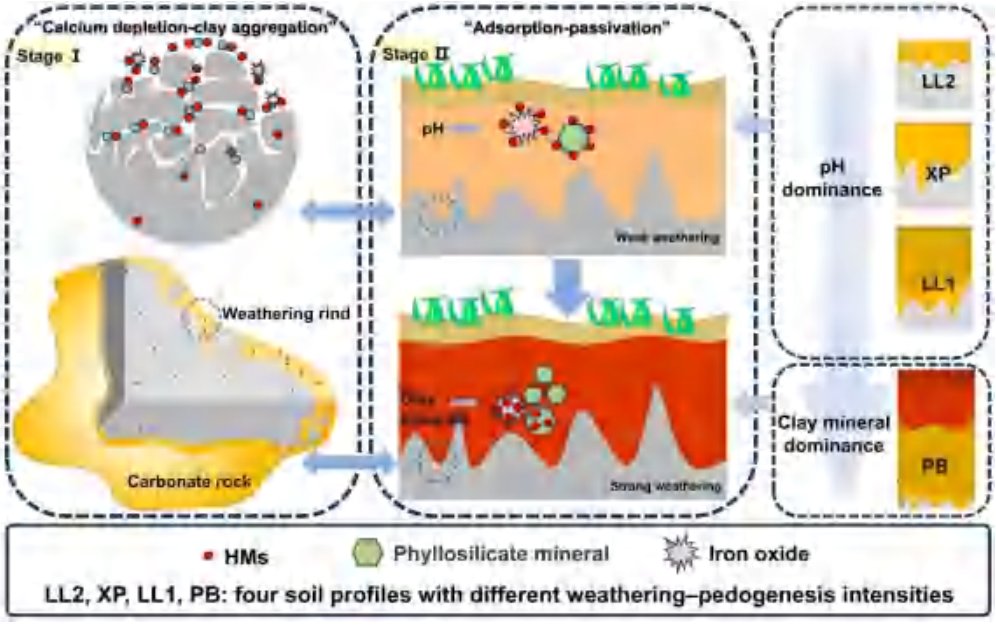
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## ABSTRACT

Carbonate rock weathering could lead to selective enrichment of heavy metals (HMs), posing potential ecological risks, however, the geochemical behavior of HMs and the dominant controls on chemical weathering within the soil-rock systems remain incompletely understood. This study systematically investigated four soil profiles at different pedogenic stages and weathering rinds at the soil-rock interface in a representative karst region of China, focusing on Cd, Cr, Cu, Pb, Zn, and Ni. Bulk concentrations and sequential extraction results showed that both total contents and residual fractions of these HMs increased with pedogenesis. In-situ microanalyses of the soil-rock interface, using LA-ICP-MS and SEM-EDS, revealed marked increases in Al, Si, Fe and HMs, accompanied by Ca depletion, from bedrock to weathering rinds. Redundancy analysis (RDA) indicated that pH and clay minerals exerted key controls on HMs accumulation across pedogenic stages. Integrating macro- and micro-scale evidence, we proposed a two-stage enrichment pattern: during early carbonate dissolution, HMs were concentrated due to Ca leaching and clay mineral formation; subsequently, elevated soil pH facilitated further enrichment, while ongoing pedogenesis promoted their encapsulation or structural incorporation into clays. These findings provide critical insights into heavy-metal dynamics in karst soils and establish a theoretical basis for pollution control and risk assessment in carbonate terrains.




**Acknowledgments**

We gratefully acknowledge Researcher Fenglan Xu and Dr. Dongling Wang at the Analytical and Testing Center of Sichuan University for their strong support in soil mineralogical analyses and heavy metal concentration measurements. We also thank Prof. David Smith of the U.S. Geological Survey for providing U.S. soil geochemical data, which greatly facilitated the establishment of the global soil heavy metal database. Technical support for LA-ICP-MS analyses from Wuhan SampleSolution Analytical Technology Co., Ltd. is sincerely appreciated. We further express our gratitude to Ms. Han Liu, Dr. Xinyue Zhao, and Ms. Xiu Zeng from Sichuan University for their invaluable assistance with field sampling and laboratory experiments.

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# Assessment of Livestock Carrying Capacity in Typical Agro-Pastoral Transition Zones Based on Heavy Metal Pollution in Cultivated Land: The Case of Chifeng City

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## ABSTRACT

Soil heavy metal pollution has become a global environmental issue due to its toxicity, cumulative nature, and resistance to degradation. As a significant agro-pastoral transition zone in northern China, Chifeng City features extensive livestock farming and high utilization rates of animal manure resources. However, heavy metals in manure entering the soil through field application may pose pollution risks. This study assessed the current status and potential risks of soil heavy metal pollution in Chifeng City by calculating the static environmental capacity (ΔQ), heavy metal input from livestock manure (Qo), and the livestock carrying capacity of cultivated land (LCCF), based on data from the 2013 and 2023 Chifeng City Statistical Yearbooks and relevant literature. Results indicate: (1) The environmental static capacities for cadmium (Cd), chromium (Cr), lead (Pb), arsenic (As), and mercury (Hg) exhibit a trend of higher environmental static capacity in the eastern region and lower capacity in the western region. Notably, the environmental capacity for Cd has significantly decreased, dropping from a maximum capacity of 27.38 kg (2013) to a maximum of only 1.63 kg (2023). The continuous accumulation of livestock manure production has resulted in input levels exceeding soil carrying capacity. (2) Among heavy metals generated from livestock manure, the primary pollution contribution areas for Cd, Cr, and As shifted from Songshan District, Wengniute Banner, and Aohan Banner to Aohan Banner, while Pb and Hg were mainly concentrated in Ningcheng County and Karqin Banner; (3) Analysis of livestock carrying capacity on cultivated land indicates Cd has already exceeded standards, with Songshan District showing the highest excess (97 pig equivalents per hectare); (4) Analysis of livestock carrying capacity across different crops reveals oilseed crops have the highest capacity (45,029 pig equivalents per hectare) due to straw removing a significant amount of heavy metals. In summary, the primary risk of soil heavy metal contamination in Chifeng City stems from increased input due to livestock manure application to farmland, with particularly prominent issues of reduced environmental capacity for Cd and regional exceedances. It is recommended to rationally optimize livestock farming layouts based on the heavy metal carrying capacity of farmland, achieving "farming determined by land capacity."

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# Mining-induced arsenic contamination: cascading effects on soil biogeochemistry, microbial community structure and human health risks

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**ABSTRACT**

Mica mining in Jharkhand, India, has led to elevated arsenic (As) contamination and altered soil biogeochemistry in surrounding agricultural fields, raising concerns about crop safety, ecological health, and dietary exposure risks. This integrated study assessed soil, rice grain, and microbial responses due to active mining. Total soil As was substantially higher in agricultural zones near the mines ($44.74 \pm 1.01$ mg kg$^{-1}$) than in the control zone ($4.79 \pm 0.11$ mg kg$^{-1}$). Subsequently, rice grains gown on the contaminated areas accumulated markedly more As ($1.09 \pm 0.08$ mg kg$^{-1}$) than the control zone ($0.11 \pm 0.02$ mg kg$^{-1}$). Sequential extraction revealed that As predominantly occurred in amorphous iron oxide-bound fractions and crystalline iron oxides, as compared to exchangeable and water-soluble phases; the amorphous fraction showed a significant positive correlation ($p < 0.05$) with As accumulation in rice tissues. Geostatistical mapping indicated that the spatial distribution of soil acidity closely mirrored that of As, suggesting a causal interaction between acidification and metalloid mobility. Soil biochemical indicators, including fluorescein diacetate, dehydrogenase, β-1,4-glucosidase, phosphatase, urease activities, along with basal respiration and microbial biomass carbon, were significantly inhibited in the contaminated zone. Metagenomics demonstrated pronounced reductions in both alpha and beta diversity in the contaminated zone, reflecting disruption of microbial community structure and functional potential. Human health risk assessment revealed total cancer risk values for children ($3.10 \times 10^{-2}$), men ($7.7 \times 10^{-3}$), and women ($8.4 \times 10^{-3}$), all exceeding the acceptable threshold ($10^{-5}$), although hazard indices for non-carcinogenic effects remained below toxic limits, with children being most vulnerable. Overall, the combined chemical, biochemical, and metagenomics evidence underscores the severe ecological and health risks posed by mining-induced As contamination. The insights gained provide a mechanistic understanding of soil-plant-microbe interactions under metalloid and acidity stress, offering a foundation for developing remediation strategies and promoting sustainable agricultural practices in mining-impacted landscapes.

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# Impact of human activities on soil heavy metal pollution and its potential ecological risks of hills within Guangzhou

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## ABSTRACT

Hills around metropolis are regarded as ecological protective screens. At south China, such hills are always cultivated for planting tropical fruits or backyard vegetables. As well known, soil heavy metal pollution has becoming more and more serious during last decades (Hou et al, 2025). Soils of such hills were influenced by human activities and conversely have impact on urban environment even human health of the residence. Therefore, it is of significant importance for pollution control land management to assess soil heavy metal pollution and its potential ecological risks for hills within cities.

In order to reveal soil heavy metal pollution status and its influencing factors, one hundred topsoil samples collected from top to bottom hill transects of a backyard vegetable plantation (ZCPT, 18 samples), a newly developed orchard (CHWQ, 32 samples), a long-time Litchi orchard (ZCGC, 15 samples), upper (ZCZX-up, 23) and lower (ZCZX-down, 12) parts of a machine plowing path within a tens-year Litchi orchard were selected for heavy metal (including Cu, Zn, Ni, Pb, Cr, Cd, As, and Hg) content measurements. Consequently, heavy metal pollution and its potential ecological risks were assessed using geoaccumulation index ($I_{geo}$) and potential ecological risk index ($E^i_r$, RI), respectively.

Although all measured samples are belonged to acid soils, soil pH values of CHWQ are significantly higher than those of other areas, indicating some subsoils were overturned to surface layer during the consolidation process. The results indicate that hill soils are contaminated by heavy metals Cu, Zn, Pb, and Cd at different degrees. The $I_{geo}$ results reveal that all measured soil samples were suffered moderately to highly Cd pollution. Lightly soil Zn and Pb pollution are appeared at CHWQ and ZCPT, respectively. Soils within ZCZX-up are suffered lightly Cu pollution and moderately to highly Pb pollution. No obvious ecological risks are caused by the mentions Cu, Zn, and Pb pollution due to the less than 40 of $E^i_r$ values. However, the mentioned Cd pollution caused considerable and moderate ecological risks for soils within ZCGC and other areas, respectively due to calculated RI values.

Since both Igeo and $E^i_r$ values of Zn are significantly positive related with pH values and Zn pollution is only appeared at the newly developed orchard and, it can be deduced that soil Zn may be related to machinery or the overturned subsoils during orchard development. The Cd pollution degree and its ecological risks of soils within the long-time Litchi orchard (ZCGC) are obviously more seriously than those of other areas, indicating the controlled impact of long-term continuous fertilization, which is consistent with conclusion suggested by many previous studies (Fei et al, 2022; ). Notably, Cd contents of samples collected from flat grounds are significantly higher than those from slopes. Furthermore, soil Cd contents of ZCZX-down are obvious higher than those of ZCZX-up. These results indicate the vertical transportation of heavy metal Cd under acid conditions and enrichment in flat areas, which is further proved the speculation by Bi et al (2025).

**Acknowledgments** This study was partially supported by the Guangzhou Land Resources and Planning Commission (Grant No. GSZB22C0025G) and the Natural Science Foundation of China (Grant No. 41977261).

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# Arbuscular Mycorrhizal Fungi and Iron-Modified Peat Synergistically Drive Soil Metal(loid) Immobilization and Organic Carbon Stabilization

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**ABSTRACT**

Soil metal(loid) contamination (e.g., Pb, Zn, Cd) threatens agricultural safety in mining regions. Conventional remediation often sacrifices soil organic matter (SOM) for metal immobilization. Developing strategies that concurrently reduce soil metal(loid) bioavailability and enhance soil carbon sequestration is crucial. Arbuscular mycorrhizal fungi (AMF) immobilize soil metal(loid) and contribute to SOM, while iron-modified woody peat (Fe-Pt) provides strong heavy metals sorption sites. However, mechanistic evidence for their combined effects on organic carbon (OC) stabilization and soil metal(loid) fate within soil microstructure is limited.

This study investigated the synergy between AMF and Fe-Pt in co-achieving soil metal(loid) immobilization and OC sequestration in a Cd/Pb/Zn contaminated soil. We hypothesized that co-application would (1) enhance microaggregate formation and mineral-associated organic matter (MAOM) accumulation, (2) promote poorly crystalline Fe phases (e.g., ferrihydrite), and (3) lead to soil metal(loid) co-stabilization within MAOM. A factorial pot experiment with *Phaseolus vulgaris* L.combined Fe-Pt addition (0 or 2% w/w) and three AMF species (Rhizophagus irregularis—AMF1, Acaulospora scrobiculata—AMF2, Gigaspora margarita—AMF3). After six weeks, plant soil metal(loid) uptake, soil aggregates, OC fractionation (POM/MAOM), Fe/Zn speciation (XAFS), and microaggregate organic functional groups (SR-FTIR) were analyzed.

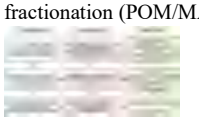


Figure 1 Diagram showing the structure organization of the present study, including the logical links among the research questions, research objectives, and methods and data.

Fe-Pt+AMF1 most effectively reduced plant Cd, Pb, and Zn uptake. Fe-Pt increased microaggregate proportion (from 39.79% to 47.48%) and total OC, with Fe-Pt+AMF1 further enhancing OC storage in MAOM. Fe k-edge EXAFS showed Fe-Pt+AMF1 promoted ferrihydrite formation while reducing hematite. SR-FTIR revealed a strong correlation between clay O–H and carboxyl/aromatic C (~ 1650 $cm^{-1}$) in microaggregates. Soil metal(loid) were preferentially enriched in MAOM, especially in Fe-Pt+AMF1. Zn k-edge XANES indicated Fe-Pt+AMF treatments decreased soluble Zn-goslarite and increased stable Zn-junitoite.



Figure 2 XRD spectra of the soils from different treatments (a), Fe species of soils from different treatments shown by Fe K edge XANES spectroscopy (b), the original (solid line) and linear combination fitted (LCF) (dashed line) k space Fe K edge EXAFS spectra of soils from different treatments (c), and distribution of Fe species in differently treated soils (d).

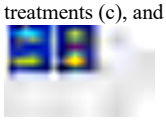


Figure 3 FTIR mapping of the microaggregate of Fe-Pt+AMF1 treatment.

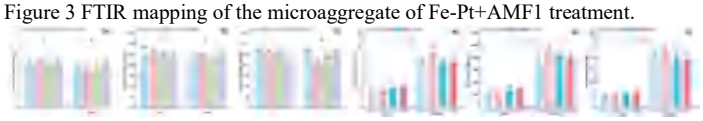


Figure 4 The contents of AAO extractable Cd (AAO- Cd) (a), Pb (AAO- Pb) (b) and Zn (AAO-Zn) (c) of soils from different treatments; the contents of total Cd, Pb and Zn (d-f) of POM and MAOM from Fe-Pt+AMF1 treatment.



Figure 5 The original (solid line) and linear combination fitted (LCF) (dashed line) k space Zn K edge XANES spectra of soils from different treatments (a), and distribution of Zn species in differently treated soils (b).

In conclusion, Fe-Pt+AMF1 synergistically immobilized soil metal(loid) and sequestered OC via: (i) Fe-Pt reducing soil metal(loid) stress on AMF, (ii) AMF-derived carboxyl/aromatic OC promoting MAOM, and (iii) Fe-Pt driving ferrihydrite formation, providing surfaces for OC and soil metal(loid) binding. This biotic–abiotic synergy enables coupled soil metal(loid) stabilization and OC sequestration within MAOM, offering a multifunctional remediation strategy for contaminated soils.



Figure 6 Conceptual model of "Organic Carbon-Soil Metal(loid)" coupling stability in the AMF-Fe-Pt system.

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# Iron (hydr)oxide-enriched Biochar for Arsenic Immobilization under Microbial Iron Reduction and Fluctuating Redox Conditions

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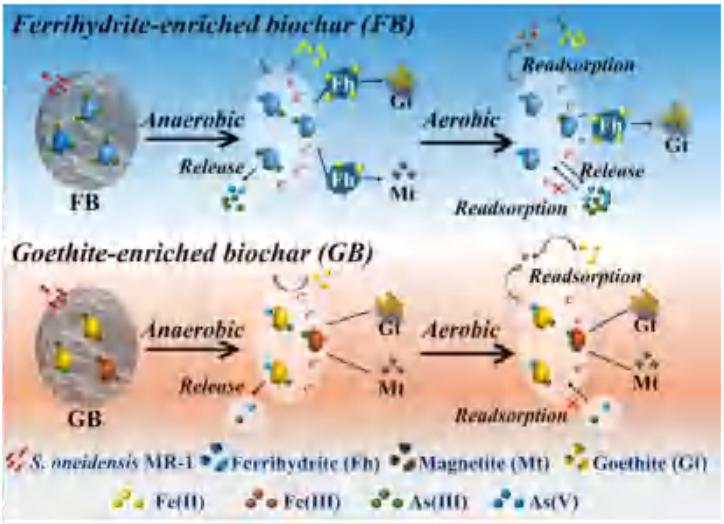
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## ABSTRACT

Iron (hydr)oxide-enriched biochar (IEB) is a material with significant environmental applications, demonstrating considerable potential in soil remediation, pollutant immobilization, greenhouse gas emissions, and carbon sequestration. However, the stability of arsenic (As) immobilized by IEBs with different crystalline structures under redox fluctuations, as well as the role of dissimilatory iron-reducing bacteria (DIRB) in mediating the biotransformation of iron (hydr)oxides within IEBs and subsequent As retention, remain poorly understood. This study investigated the effects and mechanisms of Shewanella oneidensis MR-1 (MR-1) on As retention in ferrihydrite- and goethite-enriched biochar (FB and GB) during anaerobic and aerobic transitions and evaluated the passivation capabilities of the IEB in real flooding-drying As-contaminated soils. The results from batch experiments revealed that MR-1 did not significantly affect As retention in crystalline GB. However, during the 9 days anaerobic-aerobic cultivation period, MR-1 colonization of FBs increased ferrihydrite reduction and biotransformation, increasing electrostatic repulsion and leading to a 27.2% to 88.2% increase in dissolved As compared with the sterile control. Compared with the control, both FB and GB effectively reduced the amount of water-soluble As by 44.8% and 51.0%, respectively, after 100 days of flooding–drying incubation. The more stable passivation effect of GB also mitigated the adverse effects of As on pak-choi seed germination and growth. These findings provide valuable insights into how DIRB influences As retention in IEBs, highlighting the potential of crystalline IEBs as environmentally friendly and effective materials for passivating As in soils experiencing alternating flooding and drying conditions.




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Yihao Wang and Jianying Shang, Iron (Hydr)oxide-Enriched Biochar for Arsenic Immobilization Under Microbial Iron Reduction and Fluctuating Redox Conditions, ACS ES&T Engineering, 5 (2025) 1809-1820.

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# Land-Use-Driven Patterns of Heavy Metal Contamination in Surface Soils

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**ABSTRACT**

Heavy metal contamination of soils is an increasing environmental concern in regions experiencing rapid land-use change, intensive agriculture, industrial development, and mineral exploitation. This study quantified the distribution, dominant contaminants, and integrated pollution levels of heavy metals in surface soils (0–30 cm) across major land-use types in Lam Dong Province, Central Highlands of Vietnam. A total of 235 soil samples were collected from landfill sites, industrial land (CN), perennial crop systems (coffee and tea plantations), paddy fields, vegetable–flower cultivation areas, and bauxite mining zones. Concentrations of arsenic (As), copper (Cu), lead (Pb), zinc (Zn), chromium (Cr), and cadmium (Cd) were determined, and overall contamination was assessed using a Heavy Pollution Index (HPI). Across all land uses, Zn and Cr were the most abundant metals, with mean concentrations of 58.8 and 70.5 mg $kg^{-1}$, respectively, whereas Cd occurred at consistently low levels (0.30 mg $kg^{-1}$). Landfill soils exhibited the highest metal enrichment, particularly for Cu (97.5 mg $kg^{-1}$), Zn (162.6 mg $kg^{-1}$), and Pb (31.7 mg $kg^{-1}$), resulting in the highest HPI value (51.8). Industrial soils were characterized by Cr dominance (75.8 mg $kg^{-1}$), reflecting industrial emissions and long-term accumulation. In agricultural systems, perennial crops showed elevated Cr levels, with tea plantation soils reaching 129.8 mg $kg^{-1}$, exceeding regulatory thresholds. In contrast, arsenic was the primary contaminant in annual cropping systems, especially in vegetable and flower soils where As averaged 28.4 mg $kg^{-1}$, surpassing the guideline value of 20 mg $kg^{-1}$. Bauxite mining soils displayed a distinct Cr-enriched signature (116.9 mg $kg^{-1}$) consistent with the geochemical characteristics of bauxite parent materials. Overall, HPI values decreased in the order of landfill > tea plantation > bauxite mining ≈ vegetable–flower systems ≈ coffee plantation > industrial land > paddy land, confirming that land-use type is a key determinant of both the magnitude and composition of heavy metal contamination in soils and underscoring the need for land-use-specific soil management and monitoring strategies.

**Key words:** Heavy metals, Land-use types, Soil contamination, Industrial and agricultural soils, Heavy Pollution Index (HPI)

# Large-scale nutrient management strategies shape acidification-induced risks for crop yields and food quality by cadmium

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## ABSTRACT

Cadmium (Cd) contamination in agricultural soils poses a growing threat to food safety and soil sustainability, particularly in intensively managed cropping systems[1,2]. Here, we reconstructed historical and future Cd dynamics in paddy soils using Qiyang County, China, as a representative case. By combining soil acidification and mass-balance modelling with scenario analysis, we quantified Cd inputs, outputs, soil accumulation, and transfer to rice affected by soil pH changes under contrasting soil types and management strategies.

Our results show that atmospheric deposition has been the dominant source of Cd input to croplands since 1985, contributing up to 80% of total inputs, while manure represents the second-largest source, particularly in calcareous soils. Soil pH strongly controlled Cd fate: in calcareous soils, over 90% of Cd inputs accumulated due to low Cd availability, whereas in non-calcareous soils only 44% accumulated, with substantial losses through crop uptake and leaching. Progressive soil acidification markedly enhanced Cd leaching, leading to net Cd depletion from non-calcareous soils and Cd concentrations in soil solution exceeding WHO water-quality guidelines at pH < 4.5.

Scenario analysis revealed clear trade-offs between soil fertility management and Cd risk mitigation. Enhancing manure recycling effectively mitigated soil acidification but substantially increased soil Cd accumulation in soil and rice grain. Liming raised soil pH and reduced Cd uptake by rice at short to medium term, yet could further enhance Cd accumulation if total Cd inputs remained high, failing to avoid Cd contamination at long term. Optimal risk mitigation required integrated management, combining liming to maintain soil pH above critical thresholds with reductions in total Cd inputs. Two contrasting mitigation pathways were identified: prioritizing reductions in manure Cd content limited manure recycling which benefits on soil fertility and agricultural sustainability, whereas prioritizing reductions in atmospheric Cd deposition allowed higher manure recycling but required stronger Cd emission controls.

Our findings highlight the central role of soil pH and Cd inputs in regulating Cd accumulation and food-chain transfer. Integrated strategies targeting fertilizer use, manure recycling, liming, and Cd emission control are essential to safeguard crop quality while maintaining soil fertility in Cd-vulnerable agroecosystems.

**Keywords:** cadmium; soil acidification; paddy soils; manure recycling; soil pH; food safety

**Acknowledgments**

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# Efficacy of Agricultural Waste-Derived Engineered Biochar on Arsenic/Iron Dynamics and Alleviating Arsenic Risk in Waterlogged Paddy Soil

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**ABSTRACT**

Arsenic (As), a highly toxic and carcinogenic metalloid, is often exceeds permissible limits in paddy soils Bangladesh. Fe-modified biochar has been reported as an effective amendment for remediating As-contaminated soils; however, its stability and influence on As/Fe dynamics under the waterlogged paddy soils is poorly understood. This study evaluated the stability and efficacy of Fe-modified biochar derived from agricultural waste, using $^{57}Fe$ stable isotope as a tracer to determine As adsorption and dissolution from waterlogged reduced soil. Sugarcane trash (St) and maize stover (Ms) were pyrolyzed (300, 500, and 700 °C) to produce five different biochar including Fe-modified, $^{57}Fe$-modified and $H_2O_2$ activated types. The Fe- and $^{57}Fe$-modified biochar were produced by loading the feedstocks with non-labeled Fe and $^{57}Fe$ solutions, respectively. The produced biochar were then activated with $H_2O_2$ by soaking the biochar into 5% $H_2O_2$ solution in a hot water bath for 6 h. The results revealed that the pyrolysis temperature has significant influence on the biochar yield, while higher yield was obtained at 300°C followed by 500°C and 700°C. 1% biochar was added to As-contaminated grey lowland soil (2.6 mg $kg^{-1}$) and incubated for 90 days under reductive conditions at 30 °C. The stability of Fe-modified biochar was evaluated by monitoring the $^{57}Fe/^{56}Fe$ ratio in soil solution. Fe-modified biochar produced at higher pyrolysis temperatures exhibited greater stability, as evidenced by lower Fe dissolution under reductive conditions. Non-activated Fe-modified biochar, particularly Ms-derived biochar produced at higher temperatures, was most effective in suppressing As dissolution. This was supported by lower total Fe and Fe(II) concentrations in soil solution and incubated soil. Higher Fe dissolution from St-derived Fe-modified biochar was confirmed by increased $^{57}Fe/^{56}Fe$ ratios in soil solution. In contrast, Ms-derived Fe-modified biochar showed lower Fe dissolution, indicating greater stability and enhanced As suppression. Earlier studies reported that the physicochemical properties of biochar depend on the feedstock material, which might be the reason behind the lower stability of St-derived biochar. Additionally, $H_2O_2$-activated normal biochar produced at lower temperature demonstrated better As suppression than activated Fe-modified biochar produced at the same temperature. Therefore, this study concludes that non-activated Fe-modified biochar derived from maize stover and produced at higher pyrolysis temperature has strong potential to effectively adsorb As and mitigate associated risks in waterlogged paddy soils. Nevertheless, stability was found to be reduced with the passage of time, suggesting a potential challenge towards long-term effectiveness of Fe-modified biochar under waterlogged conditions, which demands further research to unveil the effects of long-term and repeated application of Fe-modified biochar under reductive conditions.

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# Dual Roles of Corticiaceae Sp. ZJ 06 In Synergetic Soil Heavy Metal Immobilization and Soil Fertility Enhancement

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**ABSTRACT**

Soil contamination by multiple heavy metals, such as cadmium (Cd) and lead (Pb) is a global challenge that threatens ecology and human health. However, many remediation approaches overemphasize pollutant removal but overlook the recovery of soil multifunctionality. Here we successfully isolated a heavy metal-tolerant plant growth-promoting fungus *Corticiaceae* sp. ZJ 06 from soil, and explored its application in ecological restoration of Cd and Pb co-contaminated soil. The Corticiaceae sp. ZJ 06 showed rapid cell proliferation and strong tolerance to Cd and Pb. After inoculation of this functional strain, DTPA-extractable Cd and Pb were dramatically reduced by 85.8% and 60.2%, respectively. Importantly, residual fractions accounted for 76% and 61% of total heavy metals respectively, suggesting a long-lasting biostabilization of Cd and Pb after remediation. Furthermore, soil organic matter, total nitrogen, available nitrogen, available phosphorus, available potassium, and cation exchange capacity increased significantly by 30%, 23.8%, 86.5%, 28.7%, 204%, and 40.8%, respectively. Soil microbial diversity was increased and some functional microbes such as Basidiomycota were enriched. Genes related to nitrogen fixation, phosphorus solubilization, and potassium dissolution were significantly upregulated. Molecular mechanisms underlying carbon, nitrogen, phosphorus, and sulfur cycling were identified as key drivers of ecological restoration in heavy metal-contaminated soils. Overall, the remediated soil exhibited a coordinated improvement in soil multifunctionality, reflected by enhanced contaminant regulation, nutrient cycling, carbon sequestration, and biological functions. This work highlights a viable strategy for the ecological restoration of soils contaminated by multiple heavy metals.

# Core microbiomes of Cd-hyperaccumulators and its contribution to plant performance

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**ABSTRACT**

Plants evolve with persistent core microbiomes that extend host functional repertoires, yet the assembly patterns and functions of these communities remain insufficiently understood, limiting their application in enhancing plant performance. We investigated bacterial communities in the bulk soil, rhizosphere and root endosphere of various Cd-hyperaccumulators, and identified core microbes linked to key plant traits using 16S rRNA gene sequencing. Microbiome assembly along the soil-root continuum was predominantly shaped by plant species and compartment type rather than by soil type and pollution level, with host selection intensifying from the rhizosphere to the root endosphere. Stochastic processes dominated the assembly of endosphere generalists (59%), but less so for rhizosphere generalists (45%). We identified 24 rhizosphere and 9 root endophytic generalist species as core microbiomes, which were more strongly driven by host selection than non-core taxa. These core microbiomes were markedly enriched in their respective compartments, with over 60% consistently detected across controlled and field settings. Endophytic core microbes conferred greater biotic connectivity in cooccurrence networks and were stronger predictors of plant metal accumulation than soil-derived cores, whereas rhizosphere cores were more closely associated with plant biomass production and nitrogen and phosphorus acquisition. These compartment-specific contributions to plant phenotypic properties were further validated through SynComs with isolates of core microbes.

Furthermore, we examined the phylogenetic profiles and plant-beneficial traits of the core microbiota that consistently inhabits the rhizosphere of four divergent Cd hyperaccumulators and an accumulator. We evidenced the existence of a conserved core rhizosphere microbiota in each plant distinct from that in the non-hyperaccumulating plant. Members of Burkholderiaceae and Sphingomonas were the shared cores across hyperaccumulators and accumulators. Several keystone taxa in the rhizosphere networks were part of the core microbiota, the abundance of which was an important predictor of plant Cd accumulation. Furthermore, an inoculation experiment with synthetic communities comprising isolates belonging to the shared cores indicated that core microorganisms could facilitate plant growth and metal tolerance. Using RNA-based stable isotope probing, we discovered that abundant core taxa overlapped with active rhizobacteria utilizing root exudates, implying that the core rhizosphere microbiota assimilating plant-derived carbon may provide benefits to plant growth and host phenotype such as Cd accumulation. Our study suggests common principles underpinning hyperaccumulator microbiome interactions, where plants consistently interact with a core set of microbes contributing to host fitness and plant performance.

**Key words:** core microbiome, synthetic community, Cd accumulator, keystone taxa, heavy metal, remediation strategies

# Soil Water Regimes Control Cadmium Bioavailability and Translocation in Rice Systems

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## ABSTRACT

Cadmium (Cd) contamination of agricultural soils poses a persistent risk to food safety and human health, particularly in rice-based agroecosystems where rice (Oryza sativa L.) readily absorbs Cd and translocates it into edible grains. In paddy soils, Cd behavior is strongly regulated by hydrological conditions, as soil water status controls redox potential, soil chemistry, microbial processes, and root physiological activity. Although wetting and drying are known to affect Cd bioavailability, the mechanisms by which soil water regimes govern Cd migration and accumulation within soil–rice systems remain incompletely understood.

Here, we investigated how contrasting soil water regimes regulate Cd bioavailability, migration, and accumulation under graded Cd contamination. By integrating soil physicochemical properties, biological responses, and plant Cd accumulation patterns, we elucidated process-based mechanisms linking soil water status to Cd behavior across the soil–plant continuum.

Across all Cd levels, soil water regimes exerted dominant control over soil properties and Cd speciation. Flooded and adequately watered soils maintained reduced conditions, increased pH, and suppressed bioavailable Cd through enhanced adsorption and stabilization in low-solubility forms. In contrast, low soil moisture promoted oxidative conditions, facilitating Cd desorption and dissolution and markedly increasing Cd mobility. Consequently, soil Cd bioavailability consistently followed the order low moisture > moderate moisture > flooding.

These water-driven changes were directly reflected in plant responses. Rice grown under low soil moisture exhibited enhanced Cd uptake and increased root-to-shoot translocation, resulting in elevated grain Cd concentrations that frequently approached or exceeded food safety thresholds under moderate to high Cd exposure. Flooded conditions effectively constrained Cd entry into plants by limiting both root uptake and translocation, producing the lowest grain Cd accumulation. Moderate soil moisture achieved reduced Cd bioavailability while maintaining favorable plant growth.

Across all treatments, Cd distribution followed the order root > stem > leaf > grain, indicating that roots acted as the primary Cd sink. Translocation efficiency was strongly water-dependent, increasing under low soil moisture and decreasing under flooded conditions. At high Cd exposure, translocation efficiency declined, suggesting physiological constraints on Cd transport.

Overall, this study demonstrates that soil water regimes fundamentally govern Cd bioavailability, migration, and accumulation in soil–rice systems by regulating soil redox conditions, soil chemistry, microbial processes, and plant uptake pathways. Soil water status functions as a core environmental control shaping Cd behavior from soil chemistry to plant physiology, highlighting hydrological regulation as a key process controlling Cd risk in paddy agroecosystems.

# Aqueous and colloidal dynamics in size-fractionated paddy soil aggregates with multiple metals contaminants under redox alternations

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## ABSTRACT

Soil contamination by multiple metals is a significant concern due to the interlinked mobilization processes. The challenges in comprehending this issue arise from the poorly characterized interaction among different metals and the complexities introduced by spatial and temporal heterogeneity in soil systems. We delved into these complexities by incubating size-fractionated paddy soils under both anaerobic and aerobic conditions, utilizing a combination of techniques for aqueous and colloidal analysis (Figure 1). The contaminated paddy soil predominantly consisted of particles measuring <53 μm, 250-53 μm, and 2000-250 μm, with the <53 μm fractions exhibiting the highest concentrations of multiple metals. Interestingly, despite their higher overall content, the <53 μm fractions released fewer dissolved metals. Furthermore, glucose enhanced the release of arsenic while simultaneously promoting the sequestration of other metals such as Pb, Zn and Cu (Figure 2). Utilizing asymmetric flow field-flow fractionation, we unveiled the presence of both fine (0.3 kDa-130 kDa) and large (130 kDa-450 nm) colloidal pools, each carrying various metals with different affinities for iron minerals and organic matter (Figure 3). Our results highlighted the pivotal role of the <53 μm fraction as a significant reservoir for multiple metals contaminants in paddy soils, in which the colloidal metals were mainly associated with organic matter. These findings illuminated the size-resolved dynamics of soil metal cycling and provided insights for developing remediation strategies for metal-contaminated soil ecosystems.

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**Supporting figures**



**Figure 1.** ABSTRACT graph



**Figure 2.** Porewater dynamics of metals during the reduction and reoxidation of soil aggregates with different sizes (bulk soil, 2000-250 μm, 250-53 μm and <53 μm): the concentration of dissolved Cu (a, g), Cd (b, h), Pb (c, i), Zn (d, j), Ni (e, k) and As (f, l).



**Figure 3.** Fractogram of colloidal elements such as dissolved organic carbon (DOC), Cu, Zn, Cd, Mn, Fe, Pb, and As by the asymmetrical flow field flow fractionation of a solution of freely dispersed colloids collected at the third day of reduction in the soil aggregates with different sizes (2000-250 μm and < 53 μm).

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# Heavy Metal Contamination and associated ecological risks in Soils around Buddha Nullah drain, Punjab, India

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**ABSTRACT**

Soil pollution by heavy metals has emerged as a major environmental concern in peri-urban and industrially influenced agricultural regions, where long term anthropogenic inputs compromise soil quality and sustainability. The soils of these regions are increasingly exposed to heavy metal inputs resulting from industrial effluents, waste water irrigation, urban runoff and intensive land use. Such inputs alter soil quality and lead to pronounced spatial variability in metal accumulation. The present study evaluated the spatial distribution and contamination status of Arsenic (As), Cadmium (Cd), Chromium (Cr), Lead (Pb) and nickel (Ni) in soils around Buddha Nullah drain, Ludhiana, Punjab, India, using a combined analytical, pollution indexing and Geographic Information System (GIS) approach. About 150 geoReferencesd grid based surface (0-15 cm) and sub-surface (15-30 cm) soil samples from soils on both sides of Buddha Nullah drain were collected to determine the heavy metal pollution potential across locations exhibiting varying degrees of anthropogenic influence. The total concentrations of As, Cd, Cr, Pb and Ni were determined using standard methodologies, whereas bioavailable fractions were extracted using suitable chemical extractants to detect plant-available pools. Thematic maps showing the distribution of both total and bioavailable metal fractions were created by integrating the geographic coordinates of the sampling sites into a GIS platform and using spatial interpolation techniques. Pollution indices, such as contamination factor (CF), enrichment factor (EF), geo-accumulation index (Igeo), and pollution load index (PLI) were computed utilizing suitable background References values to evaluate contamination severity and anthropogenic enrichment. The spatial distribution of these indices facilitated the identification of sites with increased metal loading and cumulative contamination. The results demonstrated marked regional variability in heavy metal concentrations throughout the studied area. Ni and Cr were identified as the predominant metals in total concentrations, especially in soils adjacent to industrial areas and along wastewater impacted agricultural corridors, signifying significant anthropogenic contribution. The surface layer of soils showed greater metal accumulation compared to subsurface soils reflecting recent inputs and limited vertical translocation. The analysis of the pollution index corroborated these observations. The contamination factor and enrichment factor values revealed moderate to significant contamination of Ni and Cr at different locations, but Igeo categorization varied from uncontaminated to moderately contaminated for As, Cd, and Pb. The pollution load index additionally highlighted localized zones bearing cumulative heavy metal stress, predominantly due to higher levels of Ni and Cr. The combination of pollution indices with GIS-based spatial analysis proved effective in delineation of contamination hotspots and spatial patterns of heavy metal accumulation. The study establishes a spatial framework for assessing soil quality and emphasises the necessity of regular monitoring along with site-specific soil management approaches in industrially impacted agricultural landscapes.

**Keywords:** Soil Pollution, Heavy Metals, Peri-urban, Anthropogenic, Wastewater Irrigation, Spatial Distribution, Contamination Factor, Enrichment Factor, Pollution Load Index

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# Mitigation of Heavy Metal Transfer from Soil to Lettuce Using Pyrophyllite: A Soil–Plant Study

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**ABSTRACT**

Heavy metal contamination in agricultural soils poses a serious threat to food safety due to their potential uptake by edible crops. Effective remediation strategies are essential to reduce heavy metal bioavailability and limit their transfer through the soil–plant system. Aluminosilicate materials, such as pyrophyllite, have been reported to immobilize metals in the soil matrix and decrease plant accumulation.

This study evaluated the effect of pyrophyllite application on the uptake of heavy metals (Pb, Cu, Ni, Cd, Cr, Co, Mn, Fe, and Zn) by roots and leaves of lettuce **(***Lactuca sativa* 'Shangore' F1**).** Plants were grown in contaminated soil with and without pyrophyllite amendment, and metal concentrations were quantified using standard analytical techniques. Statistical analyses were performed using ANOVA followed by Tukey's post-hoc test ($p < 0.05$) to determine significant differences between treatments.

Results indicated that pyrophyllite significantly reduced Cd, Mn, Cu, Fe, and Zn concentrations in both roots and leaves compared to control plants, while Pb, Ni, Cr, and Co were largely unaffected. Reduction percentages ranged from 5% to 25% depending on the element and plant tissue. These findings demonstrate that pyrophyllite effectively limits heavy metal transfer from soil to lettuce, reducing the potential risk for human consumption and supporting its use as a practical soil remediation measure.

**Keywords:** pyrophyllite, lettuce, heavy metals, soil–plant system, remediation

# Content of trace elements and polycyclic aromatic hydrocarbons in soils of polar regions: variability across landscapes

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**ABSTRACT**

Soil is one of the most important component to investigate in sense of trace metals and polycyclic aromatic hydrocarbon pollution since it can accumulate and bond these organic and inorganic pollutants, which is especially relevant for sensitive ecosystems of the polar regions in regard of environmental risks produced by global climate change. In this work we present the results of research performed in both Arctic and Antarctic (projects from 2015 to 2025) regions with the aim of comprehensive investigation of biogeochemical features and soil pollution status in permafrost-affected soils. We will present data on detailed investigation of pollution status of soils in remote areas of the Arctic (Yamal region, Svalbard archipelago, Yakutia) and Antarctic (Bunger Hills, Schirmacher oasis, Larsemann Hills, Maritime Antarctica) regions. We found that our results on trace elements content in soils of various East Antarctic regions are not completely in agreement with the idea of practically uncontaminated Antarctic ecosystem, which was previously reported. Various human activities performed at local scale have been found as a relevant source for increase of metal levels in studied Antarctic environments. In general terms, obtained values if pollution indices (Igeo, contamination factor, degree of pollution, environmental risk, pollution load index) for trace elements were under or slightly above the 0 level, indicating low to moderate pollution of the studied soils. This study contributes new data on trace element accumulation in soils strongly influenced by ornithogenic factor. Bioaccumulation of metals in seabirds occupying the highest position in the food chain occurs, transfer of bioaccumulated metals into terrestrial ecosystems through birds excreta should be investigated in more detail. In Arctic soils we found poorly manifested eluvial-illuvial differentiation of trace elements in soil profiles of natural soils. The highest content for most of the studied trace elements has been revealed in Histic topsoil horizons (serves as a strong sorbent of microelements) as well as in anthropogenically-disturbed areas. Another reason for increased trace elements content in natural soils is connected with the formation of geochemical barrier on the superficial layer compared to the topsoil horizons. Principal component analysis allowed to estimate the probable sources of specific trace metals and their relationship with soil variables. Results of this study also revealed the predominance of light PAHs in studied soils. The content of heavy PAHs (only benzo(a)pyrene was quantified) does not exceed the maximum permissible concentrations values adopted by all Russian, Canadian, Argentinian and US legislation. At the same time, the content of benzo(a)pyrene, which is a marker of anthropogenic contamination, is relatively low or equal to 0 in soils of References landscapes.

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# Effect of polymeric materials on mobile forms of heavy metals the upper soil horizon at different levels of contamination in UmbricAlbeluvisols

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**ABSTRACT**

The model experiment shows the effect of artificial and natural sorbents, such as hydrolysed polyacrylonitrile (HYPAN), HYPAN +potassium humate (Sakhalin humate) and mycelium of species *Alternaria alternata* on the content of mobile forms of heavy metals (HM) in sod-podzolic soil (*Umbric Albeluvisols Abruptic*) before and after contamination of the copper, zinc, cadmium and lead salts. The soils were collected in the summer of 2024 near the village Chashnikovo (Moscow region, Russia). It is shown that the positive effect of treatment of contaminated soil with polymers is observed at all levels of HM load. At the same time, the greatest effect of remediation with sorbents used by the authors was observed in the presence of 'Sakhalin humate'. In general, the most effective reduction of mobile forms was observed at maximum soil contamination (in the experiment – 6 threshold limit value of HM).

**Keywords:** remediation, HYPAN, 'Sakhalin humate', *Alternaria alternata*, copper, zinc, cadmium, lead, sod-podzolic soil.

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# Electrochemical and molecular mechanisms underlying aluminum-enhanced copper homeostasis in maize roots within acidic copper-contaminated soils

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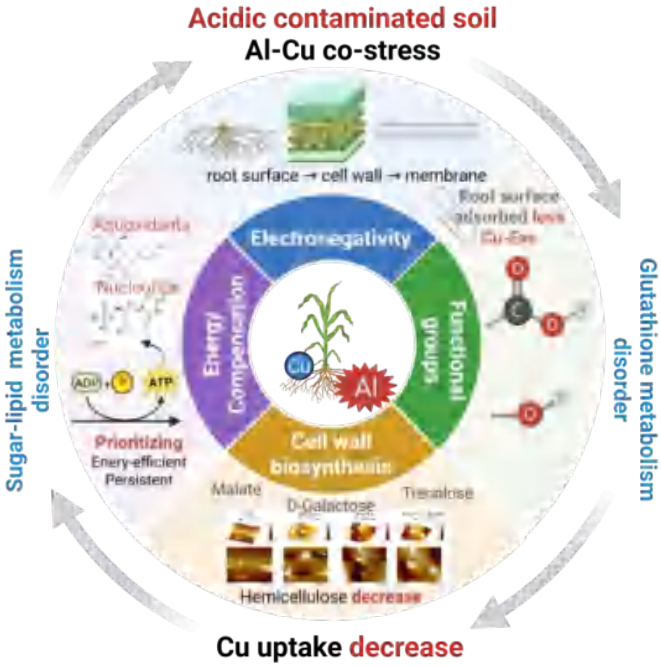
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## ABSTRACT

Copper (Cu)-contaminated soils near mining areas are typically strongly acidic, triggering substantial release of reactive aluminum (Al) from solid phases. However, Al-Cu bio-interaction effects remain understudied, despite their potential critical role. This study employed short- and long-term hydroponic experiments, along with pot trials using a Cu-contaminated soil, to investigate Al co-stress effects on Cu uptake and translocation. A multiscale approach integrating the streaming potential, zeta potential, and surface electrical potential was employed to characterize charge properties across the root surface-cell wall-cell membrane continuum. Advanced spectroscopic and metabolic techniques were integrated to elucidate the electrochemical and molecular mechanisms underlying Al-mediated Cu uptake. Results showed that Al co-stress reduced the amount of exchangeable Cu on maize root surfaces and inhibited its absorption and translocation. The coordinated decrease in electronegativity and functional group abundance of root continuum was the key electrochemical adaptation mechanism. D-galactose, malate and trehalose were critical regulators of hemicellulose biosynthesis and cell wall remodeling. Disorders in sugar-lipid and glutathione metabolism activated energy-priority survival strategy, prioritizing the synthesis of energy-efficient and persistent antioxidants (e.g. vitexin) and nucleotide to sustain cellular homeostasis. This study provides potential target metabolites and electronegativity adjustment strategies for improving crop adaptation to acidic polluted environments.

**Keywords:** Maize adaptability, root metabolite, root electronegativity, copper uptake, aluminum-copper interaction



# Multiscale Risks-Bioaccessibility Coupling Framework for Improving Derivation of Soil Cadmium Threshold

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**ABSTRACT**

It is imperative to derive the precise threshold of cadmium (Cd) in soil for rice safety production and human health protection. The traditional soil Cd threshold derivation is mainly based on the total amount of Cd and a single risk of Cd pollution, without considering Cd bioaccessibility, multiscale risks and spatial heterogeneity. This fails to synergistically protect safe rice production and human health, and often lead to over- and non-protection issues. Here, we conducted a systematic peri-urban soil-rice grain paired field sampling in the largest megacity of China, where a new multiscale risks-bioaccessibility coupling (MRBC) framework was established to improve the derivation of regional-specific soil Cd threshold. The framework is valid and reliable when applied to regional field-collected datasets. Soil Cd threshold is tailored based on soil properties, multiple risks protection objectives and bioaccessibility of Cd. Results indicated that pH, EC, and SOM concentration were major soil factors influencing the Cd bioaccumulation of rice and soil Cd threshold. Derived soil Cd threshold concentration considering $HNO_3$ and $CaCl_2$-extractable Cd decreased. However, when further considering the health risks of Cd intake through soil-rice-human transfer chain, integrating the gastrointestinal bioaccessibility significantly increased soil Cd threshold. Overall, the derived soil Cd threshold based on MRBC framework indicated that the current soil Cd environmental criteria in China were too conservative and may over-protect the regional-specific rice production and human health. Our findings improved existing soil threshold derivation techniques and enabled more precise and scientific soil environmental quality management.

**Acknowledgments**

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# Restricting roles of arbuscular mycorrhizal fungi in cadmium uptake and translocation in rice

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**ABSTRACT**

The cadmium (Cd) uptake inhibition mediated by mycorrhizal symbiosis is a highly promising phytoremediation strategy characterized by ecological friendliness, targeted regulation, and synergistic efficiency, yet its underlying mechanisms remain incompletely understood. This study employed a multidisciplinary approach integrating physiological analysis, Cd translocation characterization, and transcriptomics to systematically elucidate the molecular mechanisms by which arbuscular mycorrhizal fungi (AMF) inhibit Cd uptake and translocation in rice. The results showed that under Cd stress, AMF successfully colonized rice roots, inhibited Cd influx at root tips (50%-52%) and xylem Cd loading (52%), restricted Cd translocation to shoots, and significantly reduced Cd concentration in roots (31%) and shoots (68%). Concurrently, AMF regulated the translocation of nutrients such as P 、Ca 、Zn and Cu to maintain ionic homeostasis, alleviated Cd-induced damage to leaf cellular structure, and improved photosynthetic performance. Transcriptomic analysis revealed AMF-driven molecular reprogramming in plants: downregulating the expression of metal uptake transporter genes (*OsCAX3/8*) and translocation-related genes (*OsCCX2*), while upregulating vacuolar sequestration genes (*ABCC9/HMA3/VIT2*) and efflux genes (ABCG52/14/48). Furthermore, AMF modulated ionic homeostasis through arbuscular mycorrhiza-specific induced genes (*OsPT11*, *OsHA1*) and other transporter genes (*CCX3/ZIP5/COPT4*, etc.). This study clarifies the multi-level regulatory mechanisms by which AMF alleviates Cd stress in rice, providing an important theoretical foundation for the application of AMF in the phytoremediation of Cd-contaminated soils and the sustainable production of safe crops.

**Acknowledgments**

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# Tracing Cadmium Migration and Transformation from Atmospheric Deposition to Rice via Isotopic Fingerprinting

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**ABSTRACT**

Atmospheric deposition is a major pathway for cadmium (Cd) input into agricultural ecosystems, yet quantifying its contribution to crop uptake remains challenging. This study integrated field open-top chamber experiments, greenhouse simulations, and Cd stable isotope analysis to elucidate the migration and transformation processes of atmospherically deposited Cd in soil-rice systems. Results revealed that newly deposited Cd undergoes rapid aging in soils, with its bioavailability strongly influenced by deposition type (wet/dry). Isotopic signatures demonstrated that bioavailable Cd in soil is primarily governed by dry deposition, a pattern consistently reflected in rice grains regardless of exposure pathway. Using an isotope mixing model optimized with process-specific fractionation factors, we quantified that atmospheric deposition contributed 29–65% to the soil bioavailable Cd pool. Notably, foliar uptake of atmospheric Cd contributed over 50% to rice grains, surpassing root uptake of legacy soil Cd. The study establishes Cd isotopes as a robust tool for distinguishing Cd sources and pathways, providing a refined approach for quantitative source apportionment in agroecosystems. These findings underscore the critical role of atmospheric deposition in Cd accumulation in rice and highlight the importance of emission control strategies alongside soil remediation.

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# Soil-based assessment of lead release and contamination risks associated with lead-saturated biochars

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**ABSTRACT**

Biochar has attracted increasing attention for its environmental applications, particularly in the sustainable management of agricultural and livestock wastes and the remediation of contaminated soils and waters. Owing to its high sorption capacity, biochar is widely used to remove toxic elements from contaminated water through adsorption onto its surface. However, the environmental fate of spent biochar saturated with toxic elements after use, and its suitability as a soil amendment, remain insufficiently understood. In this study, wheat straw and cattle manure biochars, along with their lead (Pb) saturated counterparts referred to as spent biochars, were applied to soil in an eight week incubation experiment to evaluate the potential risk of Pb contamination in amended soils and to examine the distribution of Pb among different geochemical fractions. The pH values of Pb saturated biochars were 37 percent and 29 percent lower than those of the original wheat straw and cattle manure biochars, respectively, indicating that Pb sorption reduced biochar alkalinity. Such pH changes may influence soil fertility, Pb mobility, and the stability of Pb associated with biochar surfaces following soil application. Overall, these results provide new insight into the environmental implications of recycling spent biochar to soil, particularly with respect to Pb stability, mobility, and bioavailability across different geochemical fractions.

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# Mechanism informed soil washing strategy for synchronized remediation of As, Cd, and Pb

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## ABSTRACT

Synchronized soil washing of arsenic (As) together with cadmium (Cd) and lead (Pb) remains a major challenge in remediation of brownfield soils, as improvements in cationic metal extraction often fail to achieve proportional enhancement in As removal due to fundamentally different geochemical behavior and removal controls. The mechanistic basis of this mismatch remains insufficiently resolved.

In this study, a carboxyl-based composite eluent (OG), composed of oxalic acid (OA) and the biodegradable chelator tetrasodium salt of N,N-bis(carboxymethyl)-L-glutamic acid (GLDA), was developed and evaluated using naturally contaminated site soils spanning acidic, neutral, and alkaline conditions. Under optimized conditions (0.1 mol·$L^{-1}$ OA blended with 0.2 mol·$L^{-1}$ GLDA at equal volumes, pH 4, 2 h), OG exhibited a pronounced synergistic effect on As removal in soils, increasing extraction by approximately two-fold relative to OA alone and nearly one order of magnitude relative to GLDA alone ($p< 0.05$), while simultaneously strengthening Cd and Pb removal. This enabled coordinated removal of anionic and cationic contaminants beyond the additive performance of individual washing agents. Mechanistic analyses indicate that the observed synergy arises from coupled dissolution-complexation processes rather than enhanced aqueous transport. OA promotes ligand-induced and partial reductive dissolution of Fe/Al-associated As-bearing mineral phases, whereas GLDA stabilizes dissolved metal species through complexation and suppresses secondary immobilization of As. Notably, the magnitude of synergistic As enhancement declined with increasing soil pH, despite elevated apparent As mobility under alkaline conditions, as pH-dependent carrier stability progressively constrained mineral dissolution and redefined the rate-limiting step for As extraction.

From a remediation strategy perspective, these findings demonstrate that effective synchronized soil washing requires targeting pH-dependent carrier stability in addition to contaminant speciation. The proposed composite eluent provides a mechanism informed framework for remediating As, Cd and Pb co-contaminated brownfield soils under relatively mild chemical conditions, while clarifying the boundaries within which synergistic enhancement can be maximized.

# Long-term organic fertilization reduces cadmium bioavailability via enhanced binding to organic fractions and Fe-bearing minerals

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**ABSTRACT**

Fertilizers provide essential plant nutrients but may introduce toxic cadmium (Cd), posing soil ecosystem risks. However, mechanisms governing Cd mobility and stabilization under different fertilization regimes remain unclear. In this study, soils from a 27-year field experiment were investigated under three treatments: inorganic fertilizer only (NPK), inorganic fertilizer with pig manure (NPKM), and no fertilizer (CK). Total and bioavailable Cd were quantified using chemical extraction and the diffusive gradients in thin films technique. Results indicated that NPKM increased total soil Cd 5-fold relative to NPK, but the proportion of bioavailable Cd (bioavailable Cd/total Cd) was 4-fold lower. Dissolved organic matter incubation coupled with Fourier transform infrared (FTIR) spectroscopy, two-dimensional correlation spectroscopy, and Fe K-edge X-ray absorption fine structure (Fe-XAFS) revealed that NPKM promoted the formation of active soil minerals, particularly reactive Fe-bearing minerals, and altered Cd-binding sequences in soil functional groups. In NPKM soils, wavelet analysis indicated atomic-scale Fe-Cd coordination (R = ~1.8 Å, k = ~12 Å−1), suggesting that Fe–bearing minerals served as nucleation sites for Fe-Cd cluster formation. Synchrotron radiation-based FTIR spectroscopy (SR-FTIR) further demonstrated strong correlations ($p < 0.0001$, r2 = 0.34–0.85) between organic and inorganic functional groups, indicating that Fe–Cd clusters co-assembled with organic matter into stable organo-mineral complexes. These complexes effectively immobilized Cd, thereby reducing its mobility. This study established a novel multi-spectroscopy approach for elucidating Cd-binding mechanisms in soils, providing new insights into sustainable agriculture and soil remediation.

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# Arbuscular mycorrhiza orchestrates phenotypic plasticity of a critical suite of functional traits in plants under vanadium stress

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**ABSTRACT**

Vanadium (V) pollution in soil is a serious problem in some parts of China. Arbuscular mycorrhizal fungi (AMF) have shown promise in improving the remediation of V-polluted soil, but their role in orchestrating the complex phenotypic plasticity of plants under V stress remains poorly understood. We used the green foxtail （*Setaria viridis*） as the tested plant and
set three levels of soil V pollution: low (150 mg V $kg^{-1}$), medium (500 mg V $kg^{-1}$), and high (1000 mg V $kg^{-1}$). By inoculating plants with (+AMF) and without (-AMF) *Rhizophagus irregularis*, two AMF treatments were created. Plant biomass, morphological characteristics, and soil and plant V concentrations were all considerably increased by AMF inoculation at all V levels. Only at high V levels did the biological enrichment factor and translocation factor increase. The cell wall (58–64%) and soluble components (24–32%) in plant leaves exhibited a larger percentage of V than the organelles (10%-15%). The +AMF plant's leaf organelle V concentration was much lower than the -AMF plant's. Furthermore, concentrations of thiol derivatives were elevated by AMF. The functional relationships between plant fitness and important characteristics, like shoot/root ratio, shoot V concentration, biological enrichment factor, root V content, and leaf concentrations of thiol derivatives, were significantly altered by AMF. Further more, AMF significantly altered the magnitude of phenotypic plasticity in traits indicted by coefficient of variation (CV) and phenotypic plasticiy index (PPI). Phenotypic differentiation is primarily driven by AMF, according to principal component analysis (PC1). Our results show that AMF functions as a master regulator of phenotypic plasticity rather than only reducing V toxicity. By coordinating a response at the organ, subcellular, and physiological levels, it improves internal detoxification. This gives the use of AMF to improve phytoremediation in V-polluted soils a mechanistic foundation.

**Keywords:** Vanadium, arbuscular mycorrhizae, subcellular distribution, chelate, soil

# Synergistic Remediation of Cadmium-Contaminated Soil and Antibiotic Resistance Gene Mitigation by Anaerobic Soil Biological Treatment

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## ABSTRACT

Antibiotic resistance genes (ARGs) are emerging environmental pollutants able to persist and disseminate in metal contaminated soils through metal induced co-selection mechanisms. Therefore, remediation of metal contamination in soils through soil management strategies has great potential in mitigation of ARGs in soil bacterial communities. In this study, Cd contaminated soil was water flooded to obtain anaerobic conditions with different organic materials (wheat straw and soybean meal) to remediate cadmium (Cd) contaminated paddy soils. The resistance profiles (including antibiotic and metal resistance determinants) and biological pollutants (including high risk ARGs, soil-borne pathogens, virulence factors (VFs)) were further evaluated using metagenomic sequencing. Our results showed that anaerobic biological treatment in soil was able to practically promote the Cd immobilization in polluted soils and the reduced Cd bioavailability (e.g. CaCl2 extracted Cd and exchangeable Cd) further decreased the relative abundance of ARGs and metal resistance genes (MRGs) in the soil bacterial community. Changes in the soil resistome were able to attributed to a changing bacterial composition and reduced oxidative stress in soil under anaerobic biological treatments. In addition, our approach was also able to effectively weaken environmental risks posed by the soil bacterial community, including high risk ARGs, soil-borne human pathogens and VFs. In conclusion, this study provides a theoretical framework and technological strategy for synchronously mitigating of both ARGs and Cd contaminations in agricultural soils, which offers significant contributions to soil health preservation and sustainable environmental management.

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# Eco-Restoration and Phytoremediation of Metal-Contaminated Soils in Arid Landscapes Using Mycorrhized Lygeum spartum

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## ABSTRACT

Plant species inhabiting industrial areas have evolved resilience in stressed environments and represent potential valuable resources for remediating polluted sites. However, data describing the potential of xeric plant species in sustainable green applications remain scarce. This study aims to evaluate the effectiveness of mycorrhiza-amended xeric plant species Lygeum spartum, in coping with arid conditions for phytoremediation and ecological restoration of degraded and contaminated lands. A six-month controlled pot experiment was conducted to assess leaf length, enzymatic activities, and secondary metabolites. Toxic metals and metalloids (TMMs) fate was evaluated using translocation factor (TF), bioaccumulation factor (BF) and removal efficiency (RE). Fungal inoculation positively impacted growth, increasing leaf size by 64.6 % and enhancing chlorophyll content - Chl a (0.73 mg g−1 DW) and Chl b (0.64 mg g−1 DW). Root uptake of Cd, Ni, Zn, Cu, Co, Cr and Pb was significantly enhanced in mycorrhizal plants ($p < 0.05$), and inoculation improved translocation of Zn, Cr and Co, with TFZn = 1.67, TFCr = 1.11 and TFCo = 1.05 respectively. Secondary metabolites included flavonoids, total phenols, glutathion-S-transferase, carotenoids, and antioxidants such as peroxidase (POD, 4.25 µmol min−1 mg−1 proteins), ascorbate peroxidase (APX, 2.14 µmol min−1 mg−1 proteins) and superoxide dismutase (SOD, 17.04 66 U mg−1 protein). However, no improvement was observed in catalase activity or free radical scavenging potential. Therefore, xeric plant species amended with mycorrhiza are effective in TMM phytoremediation in arid environments and can be used for the restoration of degraded lands. Further, mycorrhiza could be used as sink cultures for the Phyto management and sustainable eco-restoration.

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# Predicting Continental-Scale Soil Mercury Concentrations in Australia to Refine Global Frameworks

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## ABSTRACT

Mercury (Hg) is a globally distributed toxic element with well-established risks to ecosystems and human health, particularly following methylation and biomagnification in aquatic food webs. While Northern Hemisphere studies have shaped current understanding of Hg cycling, comparable continental-scale assessments in the Southern Hemisphere remain limited, constraining the accuracy of global Hg models and the development of regionally appropriate management frameworks. Australia provides a unique opportunity to address this gap due to its highly weathered soils, diverse biomes, low anthropogenic Hg emissions, and strong oceanic influence on atmospheric inputs.

We quantified background Hg concentrations and their environmental controls using fine (<75 µm) top and bottom outlet sediment samples collected at the outlet of 1,141 large catchments as part of the National Geochemical Survey of Australia, covering approximately 76% of the continent (~ 5.84 million km²). Total Hg concentrations ranged from 0.97 to 556 ng $g^{-1}$ in top outlet sediments (mean ± SD: 23.5 ± 27.5 ng $g^{-1}$) and from 0.90 to 525 ng $g^{-1}$ in bottom outlet sediments (19.1 ± 22.3 ng $g^{-1}$). More than 98% of samples were below 100 ng $g^{-1}$, indicating generally low natural Hg concentrations across Australian soils.

Spatial analyses revealed higher Hg concentrations in southeastern Australia, particularly Tasmania and temperate and Mediterranean forest biomes, and lower concentrations in arid and grassland regions. Differences among States and Territories were driven primarily by underlying soil and vegetation characteristics rather than lithology or land use alone. Organosols and ferrosols exhibited the highest Hg concentrations, reflecting strong retention by organic matter and iron-rich mineral phases.

Boosted regression trees and random forest models identified loss on ignition (proxy for soil organic matter) and an index of ferrosols as the dominant predictors of Hg concentrations, with additional contributions from soil nitrogen, lead, nickel, and vegetation structure (leaf area index). Water availability played a comparatively minor role, consistent with Australia's low runoff and highly variable rainfall. Spatial prediction at 0.005° resolution highlighted elevated Hg in forested, iron-rich soils and comparatively uniform low concentrations across much of the arid interior.

Our results demonstrate that Hg distribution in Australian soils is controlled primarily by pedogenic and biogeochemical factors rather than anthropogenic inputs, providing a robust baseline for identifying contaminated sites and future changes. This continental-scale assessment improves representation of Southern Hemisphere processes in global Hg frameworks and supports evidence-based implementation of the Minamata Convention on Mercury.

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# Sample preparation and characterize of soil dissolved organic matter

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**ABSTRACT**

Soil dissolved organic matter is one of the most active chemical components in soils, playing critical roles in governing the environmental fate, transport, behavior and toxicity of trace and heavy metals and organic containments and affecting the biogeochemical cycles of carbon and nitrogen in aquatic and terrestrial systems. The ecological function of soil DOM is affected by its chemical composition and structures. Herein, we have compared the traditional DOM extraction method with the HCl-assisted high pressure extraction using the ultrahigh-resolution mass spectrometry (e.g. Fourier transform ion cyclotron resonance mass spectrometry, FT-ICR MS). The HCl-assisted high pressure extraction method gives much higher DOC yields, but yet not affect the chemical composition of soil DOM as compared with tractional DOM extraction with ultrapure water. The Fourier transform ion cyclotron resonance mass spectrometry was further offline hyphenated with high performance liquid chromatography (HPLC) to elucidate the polarity of soil DOM in governing its disinfection byproducts formation. Much more chemical formulas were observed in the HPLC-FT-ICR MS as compared with the traditional direct infusion mode.

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# Influence of Soil Properties on the Extraction of Active Contaminant-Degrading Enzymes

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## ABSTRACT

Monitoring bioremediation often relies on tools that indirectly assess microorganism activity. These tools include genomic techniques that indicate the presence of necessary microorganisms but not necessarily the activity, and analytical techniques that confirm the degradation of contaminants but not necessarily the mechanism. Direct measurements of soil proteins and enzymes can provide the necessary information via soil proteomics. Although soil proteomics has advanced through mass spectrometry, most studies still rely on protein-denaturing extraction methods. The inability to distinguish between the catalytically active and inactive enzyme fractions in soils limits proteomic applications for bioremediation monitoring. Further, the influence of soil properties on the recovery of active enzymes is rarely considered, limiting the quantitative potential of proteomics applications. This study applied an indirect, non-denaturing extraction method; comprising (l) sucrose density gradient centrifugation to separate cells from soil, (2) sonication to lyse cells, and (3) centrifugation to recover soluble enzymes; to evaluate how soil physicochemical characteristics affect the extractability of intracellular perchlorate-reducing enzymes. Across 81 soil samples, final enzyme recoveries ranged from 0.34% to 9.91%, reflecting strong matrix-dependent variability. Spearman correlations identified pH, cation exchange capacity (CEC), and $Ca2^{+}$ as significant drivers of cell recovery, and pH, EC, % sand, CEC, $Cu2^{+}$, $Mn2^{+}$, and $Zn2^{+}$ as significant for enzyme recovery. Expanded regression modeling (linear, standardized, polynomial, and interaction models) revealed deeper mechanistic controls: $Al3^{+}$ and $Na^{+}$ were the strongest predictors of cell release, while $Al3^{+}$, $Cu2^{+}$, and $Zn2^{+}$; including nonlinear and metal–metal interactions (Al×Zn, Al×Mn, Na×Mn); explained over 45% of the variability in enzyme extraction. These patterns reflect cation bridging, ionic-strength thresholds, and clay-associated sorption effects. Together, the results demonstrate that soil chemistry exerts strong control over intracellular enzyme recovery, with implications for improving soil proteomics and enhancing the detection of active bioremediation processes.

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# Interaction mechanisms of Cr with organo-mineral complexes : Past achievements and future perspective

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**ABSTRACT**

Chromium (Cr), with high toxicity, is one of the primary controlled heavy metals in China. Understanding the soil chemistry of Cr facilitates to effectively control the mobility and bioavailability of Cr in the contaminated soil sites and agricultural lands, thus mitigating the contamination risk of underground water and crops. Organo-mineral complexes (OMC), widely present in the soil environment, have multiple active components, including metal oxides, organic matter etc., and provides active binding sites for Cr immobilization. synchrotron-based Scanning transmission X-ray microscopy (STXM) spectroscopy was demonstrated to simultaneously characterize the distribution and speciation of C, Cr, and related mineral elments (i.e. Fe), providing a unique platform to investigate the binding mechanisms of Cr and OMC. Here, we summarized the past research achievements on the interactions of Cr with organo-iron oxides complexes, particular at the molecular level using advanced synchrotron-based STXM techniques. The future perspective in this research field was also proposed according the development of synchrotron-based techniques.

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# Iron, sulfur, and carbon dynamics collectively regulate the fate of cadmium over the sulfidation-reoxidation cycle

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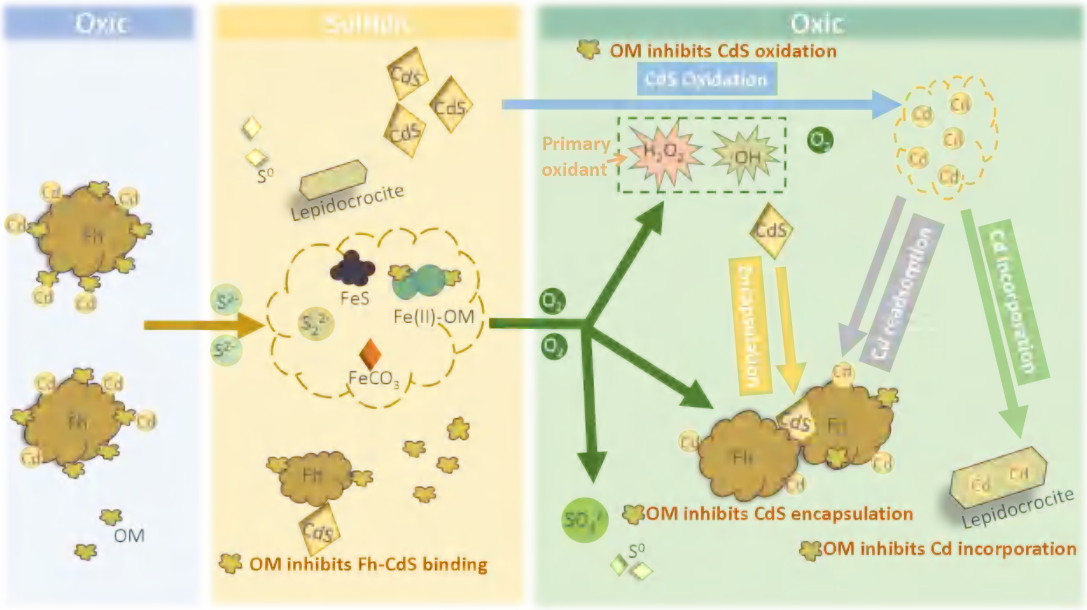
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**ABSTRACT**

Cadmium bioavailability is sensitive to redox fluctuations, with its fate linked to the coupled dynamics of Fe, S, and C. This study examines the behavior of Cd-loaded ferrihydrite (Fh) with/without organic matter (OM) undergoing S(-II)-induced reduction followed by O2-induced reoxidation. During sulfidation, S(-II) was fully consumed, and Fh was partially reduced to Fe(II) species, with some OM released from the Fh surface. Meanwhile, Cd initially adsorbed on Fh was completely converted to CdS, regardless of Cd loading or the presence of OM. Upon reoxidation, Fe(II) species were reoxidized to Fe(III) oxides, which recaptured OM, while solid-phase S(-II) was oxidized to S0 and sulfate. Concurrently, partial oxidation of CdS occurred, mainly driven by $H_2O_2$ generated during Fe(II) oxidation, with minor contributions from ·OH and O2, but OM inhibited CdS oxidation, primarily by scavenging $H_2O_2$. Released Cd from CdS oxidation was predominantly readsorbed on Fe(III) oxides. Additionally, released Cd was partially structurally incorporated into newly-formed Fe(III) oxides while some CdS was encapsulated within Fe(III) oxide aggregates. However, OM interactions with Fe(III) oxides reduced the formation of these Cd species. These findings provide insights into the molecular-scale mechanisms governing Cd dynamics in redox-dynamic environments.

**Key words:** Cadmium, iron, sulfur, organic matter, dynamics




**Acknowledgments**

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# Visualization of Organic Carbon Distribution in Soil Minerals

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**ABSTRACT**

Soil minerals play a critical role in controlling the stability and transformation of organic carbon (OC) in soil environment through both chemical and physical processes. Understanding of the mechanisms of OC sequestration by minerals is essential for predicting the OC turnover in soil. Numerous studies have shown that mineral compositions, morphology, structure are the key factors accounting for OC sequestration by minerals, but the microscopic investigation of OC interaction with minerals is complicated by the complexity of soil organic matter and dynamic properties of reactive minerals. Therefore, it is desired to directly visualize the dynamic interactions between OC and different soil minerals with high spatial resolutions.

In this talk, we will present our recent efforts in imaging the OC (and its chemical species) interactions with typical soil minerals (e.g., Fe and Mn oxides) at nano- to sub-nano scales by employing the spherical aberration corrected scanning transmission electron microscopy (Cs-STEM) coupled with electron energy loss spectroscopy (EELS). Our studies have provided mechanistic insight into the stabilization of OC during the Fe oxide transformation processes and OC distribution on Mn oxides during the coupled reactions of adsorption and oxidation. EELS results have provided direct evidence of the spatial distribution of OC and its species (e.g., carboxyl and phenol C) at the mineral surfaces and the bulk of minerals. Different OC species have shown distinct patterns of interactions with minerals, which was further affected by the dynamic composition of minerals under different environmental conditions. Our results would help to elucidate the nanoscale sequestration mechanisms of OC by various soil minerals and to develop quantitative models for OC turnover in soil environment.

**Keywords:** Soil mineral, Cs-STEM, Sequestration, Microscopic investigation

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# Freeze-thaw driven colloid release from soils: Roles of aggregate turnover and pore network

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## ABSTRACT

Soil colloids are critical yet mobile components that regulate the fate of nutrients and contaminants in the environment. However, the mechanistic links between freeze-thaw-induced soil structural changes and colloid release dynamics, particularly across seasons, are poorly quantified. We bridged this gap by simultaneously quantifying aggregate turnover via rare earth oxide tracers and 3D pore architecture via X-ray μ-CT to unravel colloid release mechanisms. We compared two distinct seasonal regimes: autumn freeze-thaw (AFT, rapid thaw) and spring freeze-thaw (SFT, gradual thaw). Results revealed a fundamental seasonal dichotomy. AFT significantly disrupted soil structure, whereas SFT had a minimal effect. AFT preferentially broke down 0.5–0.25 mm aggregates, inhibiting their re-aggregation and thereby driving colloid release from this key fraction. Colloid release was positively correlated with increased porosity, pore number, and pore branch density—metrics that were significantly enhanced by AFT but not by SFT. X-ray μ-CT visualized the creation of a vertical porosity gradient rich in macropores and elongated pores, with changes in total porosity and connectivity markedly greater under AFT. These results demonstrate that colloid release is mechanistically driven by the co-evolution of pore architecture—specifically, the development of connected macropores for transport and abundant regular small pores for colloid detachment—a process activated effectively by rapid thawing but mitigated by gradual thawing.

**Acknowledgments**

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# Molecular Mechanism of Mn Oxides driven Oxidative Decomposition and Polymerization of Litter-Derived DOM at Different pH Revealed by FT-ICR MS

**Xionghan Feng[1,2*], Feng Jiang[1,2], Hong Su, Qinglong Fu[3], Zi Yang[1,2], Xiaoming Wang[1,2], Hui Yin[1,2], Wenfeng Tan[1,2], Bruno Lanson[4]**

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**ABSTRACT**

Manganese (Mn) redox cycling critically regulates soil organic carbon (SOC) turnover, especially in the forest litter layer. However, the molecular-level mechanisms underlying the Mn oxide-mediated decomposition and polymerization of dissolved organic matter (DOM) from litter remain poorly understood. Integrating excitation–emission matrix spectroscopy (EEM) and Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS), we investigated molecular mechanisms of δ-$MnO_2$-driven transformations of natural leaf litter-derived DOM samples across an ambient pH gradient (4, 6, 8). Results reveal that δ-$MnO_2$ simultaneously drives decomposition and polymerization of DOM, with pH modulating their relative contributions. At higher pH (pH 8), δ-$MnO_2$ facilitates aromatic condensation and coupling involving Mn(IV)→Mn(III)-mediated single-electron transfer, forming highly aromatic humic-like polymers and reducing electron-donating capacity, thereby enhancing oxidative resistance. Under lower pH (pH 4), δ-$MnO_2$ drives depolymerization and aromatic ring-opening by selectively cleaving oxygen-rich aromatic species. This process is dominated by multi-electron transfer, with Mn(IV) reduced to Mn(II) via successive electron donation from DOM. Additionally, initial DOM composition impacts its transformation pathway. Specifically, high-aromaticity, high-molecular-weight fractions preferentially decompose, whereas low-aromaticity DOM tends to polymerize. These findings highlight the dual roles of Mn oxides in stabilizing organic matter, driving both the breakdown and reassembly through pH-regulated redox reactions.

**Acknowledgments**

This work is financially supported by the National Natural Science Foundation of China (Nos. 42030709, 42377303, and W2521004).

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# Elucidating the Molecular Mechanisms of Microplastics in Heavy Metal Transformation

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**ABSTRACT**

Microplastics, now pervasive across various environmental compartments, pose a significant concern due to their ability to adsorb heavy metals and, more critically, to transform their chemical forms. They can alter metal speciation via redox reactions and serve as methyl donors, thereby accelerating the methylation of mercury—a process with crucial implications for toxicity and bioaccumulation. This study aims to clarify the underlying molecular mechanisms through which microplastics mediate these transformations, utilizing cutting-edge spectroscopic and chromatographic techniques.

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Author, A.B. and Author, C.D., Paper Title, Journal Name, Volume (Year) Page Numbers.

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# Using an inexpensive RGB color sensor for field quantitative assessment of soil accessible Cu(II)

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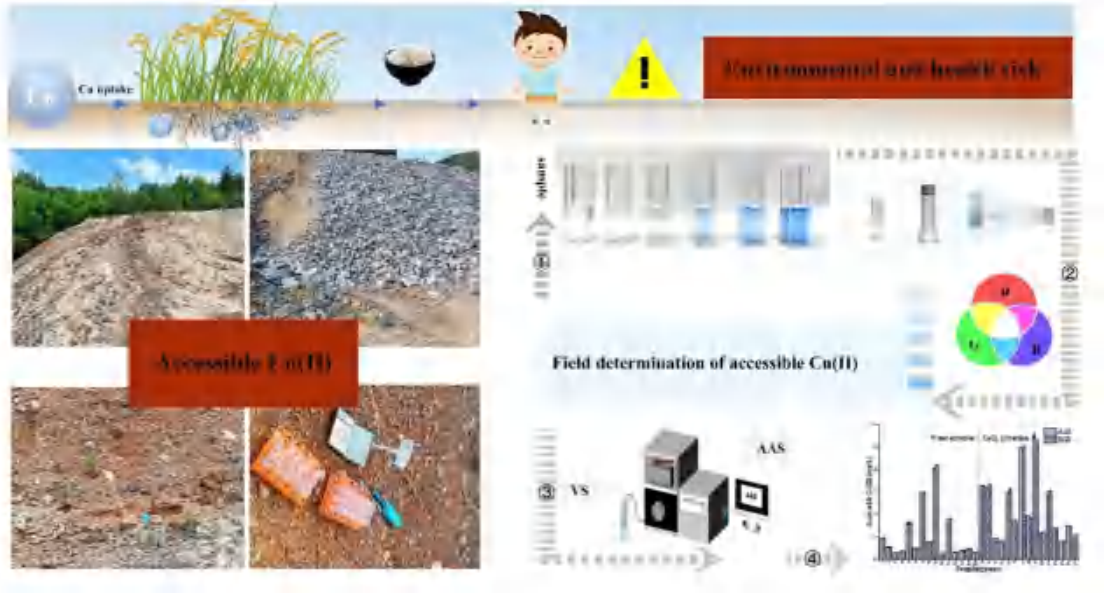
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## ABSTRACT

Field rapid determination of soil accessible Cu(II) was important for environmental safety and human health risk assessment. In this study, an inexpensive red, green, and blue (RGB) color sensor was used for quantitative color difference analysis of the colored solution for soil accessible Cu(II) with bis-cyclohexanone oxalydihydrazone as color reagent to develop a new method for analyzing soil accessible under field conditions. First, the calibration curve for RGB color sensor method was established in the standard solutions of Cu(II). Then the "hand shaking + standing" field extraction method for accessible Cu(II) was developed. Finally, the method was applied in contaminated soils in the laboratory and in the field, and set the values determined by atomic absorption spectroscopy (AAS) as the standard ones. Results indicated that in the range of 0.1–5 mg·L$^{-1}$ Cu(II), the RGB Euclidean chromogenic difference values were directly linear correlated with the concentration of Cu(II) ($R^2 > 0.999$). The interference of Fe(III) and Mn(II) could be eliminated by adding citric acid. The "hand shaking + standing" field extraction method could effectively extract the accessible Cu(II) from soil with the high extraction rates. The concentrations of accessible Cu(II) in various polluted soils determined by RGB color sensor method were consistent with that determined by AAS, with the relative error within ±5%, the relative standard deviation ≤ 20%. The recovery of Cu(II) in RGB color sensor method was between 97% and 105%, which could meet the requirements of trace analysis of accessible Cu(II) in the field. The high accuracy and precision of RGB color sensor method was reconfirmed in the rapid field quantitative assessment of soil accessible Cu(II). Due to that the RGB color sensor was low cost, rechargeable, portable, mobile, ambient light resistant, the method would have a great potential for the determination of accessible Cu(II) in contaminated soils.

**Keywords:** RGB color sensor; soil accessible Cu(II); bis-cyclohexanone oxalydihydrazone; field determination; polluted site soil



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# Solid Phase Molecular Diversity Enhances Soil Organic Matter Persistence

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**ABSTRACT**

Molecular diversity has been proposed as a critical factor controlling soil organic matter (SOM) persistence. However, in contrast to dissolved organic matter, molecular diversity of solid phase organic matter remains largely unexplored. Here, we show the molecular diversity features of solid phase organic matter through a direct mass spectrometric scan of particulate and mineral associated organic matter (POM and MAOM) that show a strong relationship with carbon turnover rates, collected from a long-term grassland recovery experiment after 0, 23, and 43 years. We found that the highest molecular diversity (Hill Number = 1603±124) existed in SOM that had the slowest carbon turnover rate. Molecular diversity of MAOM exhibits greater correlation ($R^2 = 0.95$, $p < 0.001$) with SOM persistence than that of POM. Molecular diversity became increasingly enriched from top to subsoil horizons (360% increase), consistent with a breaking down of large molecules into a range of low- to high-molecular-weight molecules. Soil depth and total iron content were main factors impacting the diversity change of POM and MAOM, highlighting the combined control of microbial decomposition and mineral interaction in shaping molecular features of solid phase organic matter. Together, these results suggest that molecular diversity may not operate as a limiting factor for carbon utilization by decomposers but as an ecosystem property that incorporates organo-mineral interactions.

**Acknowledgments**

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# The Role of Molecular Environmental Science in Addressing a Changing Climate

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**ABSTRACT**

The use of state-of-the-art, *in-situ* small spatial and temporal scale spectroscopic and microscopic techniques have greatly advanced our understanding of biogeochemical reactivity and speciation of contaminants and carbon in natural, heterogeneous systems such as soils, sediments, particulates, and aquatic systems. The use of synchrotron-based tools especially have been instrumental in advancing research frontiers in molecular environmental science. Recently, the use of small-scale analytical tools to address vexing questions and challenges related to climate change have provided new insights in several research areas in soil and environmental sciences including: impacts of drought on transport and toxicity of soil particulates and metal contaminants, wildfire effects on redox transformations of geogenic elements, and the role of sea level rise, flooding, and salinity on toxic metal(loid), nutrient, and carbon speciation and cycling. The geochemical aspects of these environmental change phenomena will be linked to human health as well as social issues.

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# Application of liquid chromatography coupled with FT-ICR MS for analysis of soil dissolved organic matter

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**ABSTRACT**

Soil dissolved organic matter (DOM) is a crucial component of the global carbon cycle. Soil DOM exhibits extensive physicochemical properties and often interacts with the abundant iron-containing minerals widely existing in the soil, thereby affecting the chemical form, bioavailability and stability of organic carbon. However, analytes at low concentrations or low ionization efficiency are difficult to detect due to the complexity of soil DOM by conventional analytical method namely direct infusion by Fourier transform ion cyclotron resonance mass spectrometry (DI-FT-ICR MS). Herein, we succeeded in fractionating of different polar organic molecules using high performance liquid chromatography (HPLC) and subsequently acquired the ultrahigh-resolution mass spectra of each concentrated fraction by FT-ICR MS. Compared with DI-FT-ICR MS, HPLC-FT-ICR MS not only identified more chemical formulas, but also improved the detection of low abundance compounds. In addition, molecular structure information of some specific soli DOM components was obtained using collision-induced dissociation for further insight into relationships between DOM and minerals in the soil. This work demonstrates that offline hyphenated of HPLC-FT-ICR MS is an effective analytical method for soil DOM characterization at the molecular level.

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# Enhanced Remediation of Herbicide-Contaminated Soils Using Phosphate-Modified Biochar

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## ABSTRACT

Given that acetochlor (ACT) persists in soil for extended periods, disrupting microbial community structure and causing phytotoxicity to sensitive crops, this study investigated the potential of phosphate-modified biochar (PBC-800) to remediate ACT-contaminated soil. Incorporating 0.5 % PBC-800 into fluvo-aquic, red, and black soils increased their adsorption capacities by 80.4 mg $g^{-1}$, 76.6 mg $g^{-1}$, and 76.0 mg $g^{-1}$, respectively. Even after six months of aging, the $K_f$ values remained 1.6 to 5.1 times higher than in untreated soils. PBC-800 also accelerated ACT degradation across all three soil types, reducing residual ACT levels by 34.3 % to 76.4 % after 60 days, and shortening the degradation half-life by 5 to 7 days. High-throughput sequencing revealed that ACT reduced soil microbial diversity and disrupted community structure, while 0.5 % PBC-800 amendments promoted the growth of degradation-capable genera such as *Rhodococcus*, *Lysobacter*, and *Gemmatimonas*, enhancing microbial ecosystem stability. Furthermore, the amendment of soil with 0.5 % PBC-800 reduced ACT residue concentrations in maize and soybeans by 76.5 % to 82.9 %, and restored plant biomass, leaf chlorophyll content, and mesophyll cell ultrastructure to levels comparable to the control. Therefore, amending ACT-contaminated soil with PBC-800 mitigates ecological and environmental risks, boosts microbial activity, and safeguards plant health.

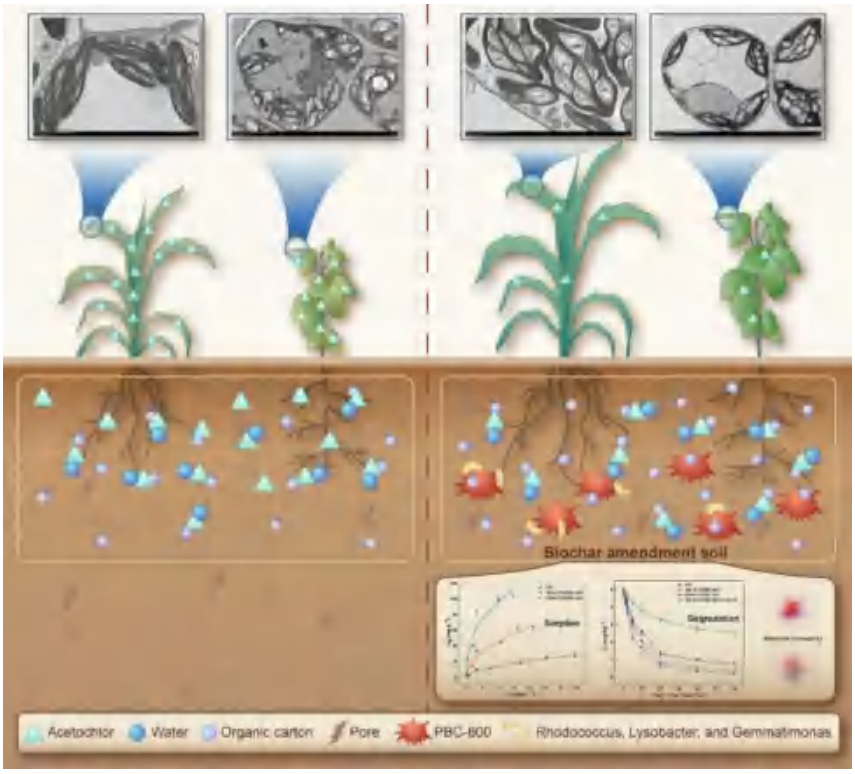



Figure ABSTRACT

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# Interactions of selenium and heavy metals in paddy systems: Mechanisms and risk assessment

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**ABSTRACT**

Selenium (Se) plays a critical role in environmental and human health, yet its interactions with other heavy metals in paddy systems remain insufficiently understood. This knowledge gap limits our ability to assess Se's environmental effects and its potential for mitigating heavy metal pollution. To address this, we systematically investigated the biogeochemical behaviors of Se and major toxic metals—including mercury (Hg), cadmium (Cd), and arsenic (As)—within the soil–rice–atmosphere continuum of paddy ecosystems[1-3].

Our results demonstrated that Se exhibits widespread antagonistic relationships with these metals, significantly reducing their accumulation in rice tissues. Such antagonism is most evident between Se and Hg, which serves as a representative example of Se–metal interactions. For the Se–Hg system, we summarized both microscopic processes and macroscopic manifestations of their interactions and proposed a dual-pump driving mechanism operating at the "soil–root" and "atmosphere–leaf" interfaces[1].. At the soil–root interface, $HS^-$ ($H_2S$), $Fe^{2+}$, and microorganisms play key roles in Se and Hg transformations through oxidation–reduction, methylation, and demethylation processes. Se also enhances the formation of iron plaques, reduces Hg absorption, and promotes HgSe complex formation, thereby limiting Hg translocation into roots. In the aboveground part, Se–Hg transformations likely occur within leaves, which serve as the main sites for Hg/Se uptake and bioaccumulation, forming the second driving mechanism.

Beyond Hg, Se shows comparable inhibitory effects on Cd and As uptake in rice. For the Se–Cd system, hydroponic experiments under gradient concentrations of Se and Cd revealed a mutual inhibition of their absorption, transport, and accumulation in rice [2,3]. The uptake of Cd decreased sharply when the molar ratio R(Se/Cd) exceeded 1, whereas Se uptake was suppressed at R(Cd/Se) greater than 20. This threshold behavior suggests that the formation of insoluble Cd–Se complexes in roots plays a key role in regulating Cd translocation. Furthermore, Se enhanced the antioxidant defense capacity of rice under Cd stress by activating enzymatic and nonenzymatic antioxidant systems. Couplings among multiple antioxidant subsystems—such as the AsA–GSH cycle, GS–PCS coupling, and GPX–SOD pathways—were identified in aerial tissues, providing a physiological basis for Se-mediated Cd detoxification.

Overall, this study elucidates the mechanisms and thresholds of Se–metal interactions in paddy ecosystems. The findings reveal Se's unique dual role as both a micronutrient and a natural regulator of heavy metal bioavailability and toxicity. These insights provide a theoretical foundation for risk assessment and for the development of Se-based soil amendments and remediation strategies to ensure safe rice production in metal-contaminated farmlands.

**Acknowledgments**

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# Model-based Rescue: Phytotoxicity Threshold and Control Strategy of Fluridone Residue on Herbicide-sensitive Rotation Maize

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## ABSTRACT

Residual fluridone (FLU) in field soil poses a significant threat to crop growth in rotation systems. Therefore, it is imperative to investigate the phytotoxicity threshold of FLU and explore solutions to mitigate damage. In this study, the effects of residual levels of FLU and its phytotoxicity in a FLU-sensitive rotation crop maize were investigated. Study at 80 field sites indicated that the average detection rate of FLU was 81.25 %, with the highest residual concentration of 5346 μg/kg dw, which could induce death in maize seedlings. We then measured the absorption of FLU by maize seedlings from soil pore water (SPW) in hydroponic experiments and obtained the no-significant-effect concentration of FLU (4.2-5.3 μg/L). To investigate the ability of rice husk biochar (RH500) to adsorb FLU in different soil environments, isothermal adsorption experiments were conducted. The results indicated that when the RH500 was increased from 0.1% to 2% (w/w) in Aksu soil, the Kd value relative to the control group increased by 1.20 to 3.82 times. Finally, a mathematical model was developed for predicting FLU concentrations in SPW from RH500-containing soil. The predicted values closely aligned with the experimental data (slope = 1.27, $R^2 > 0.9$, and mean absolute percentage error = 24.2%), indicating that the model yields predictions with a reasonable accuracy. In conclusion, we have developed an effective approach to establish a phytotoxicity threshold for residual herbicides in rotation crop systems, and we propose an RH500-based strategy to mitigate damage caused by residual FLU in soil.

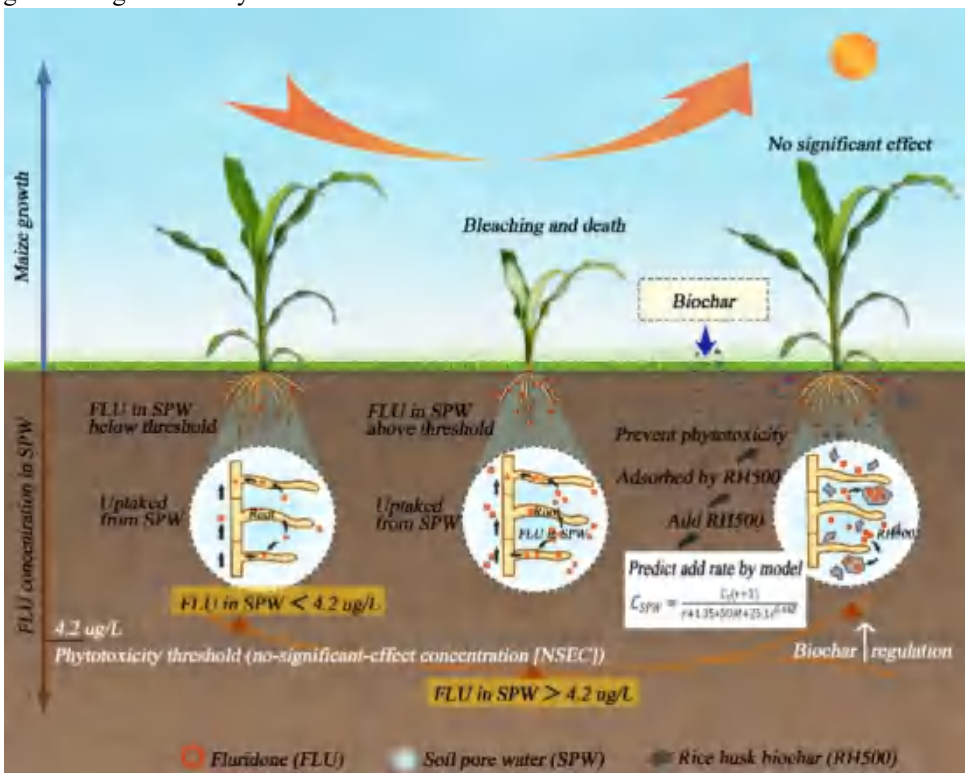



Figure ABSTRACT

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# Methods for Assessment of Risk Posed to Agricultural Lands and Food Crops by PFAS-Contaminated Sludges and Irrigation Water

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFASs) pose an increasing environmental as well as financial and legal concern for agricultural lands where wastewater and sludges have been used to irrigate fields and amend soils. A significant proportion of non-industrial wastewater and sludge has historically been applied to agricultural land. In addition to benefits for plant growth and soil restoration, reuse of wastewater and sludges provides an alternative to expensive treatment or disposal. Wastewater and sludges from industrial sources, including textile mills and paper processing facilities, have also been applied to agricultural lands in some areas due to the lack of disposal options and a shortage of clean water for crop irrigation. Regulatory controls have traditionally focused on metals that could pose a toxicity risk to plants or adverse uptake into food crops, including livestock feed, and general soil and water quality parameters such as pH and salinity. Consideration or organic contaminants in early, draft regulations was dropped after the ban of organochlorine pesticides such as DDT, toxaphene and chlordane in the 1970s and 1980s.

The identification of PFASs in both industrial and non-industrial wastewater and sludges has called into question the continued reuse of these media for agricultural operations as well as the continued use of affected fields for the cultivation of food crops. The anionic form of PFASs are normally found in the environment. Toxicity studies suggest that long-chain compounds, such as perfluorooctanoate ($PFOA^-$), perfluorooctane sulfonate ($PFOS^-$) and perfluorohexane sulfonate ($PFHxS^-$) are potentially more toxic than legacy contaminants such as polychlorinated biphenyls (PCBs). These compounds are considered "terminal" in that they are resistant to further degradation in the environment. Although less toxic in comparison, studies suggest that ultrashort and short-chain compounds such as perfluoroethanoic acid ($PFEtA^-$ or "trifluoroacetate") and perfluorobutane sulfonate ($PFBS^-$) are similar in toxicity to contaminants such as naphthalene, arsenic and cadmium. Uptake of long-chain compounds such as $PFOA^-$ into the stems and leaves of plants used for food is well documented. Uptake of ultrashort and short-chain compounds into food crops is less well studied but likely of even greater concern, due to their increased abundance in wastewater and sludges and increased mobility in the environment. Risks posed by the myriad of precursor compounds and related breakdown products that can dominate the makeup of PFASs in wastewater and sludges is even less well researched and understood. The inability of laboratories to comprehensively report all PFAS-related compounds in a sample as well as the lack of toxicity factors for the majority of precursor compounds and their metabolites necessitates development of an alternative method to assess risk.

Accurate assessment of the risk posed by PFAS-impacted agricultural lands and food crops requires careful, systematic planning and data collection, including: 1) Designation of risk-based "Decision Unit (DU)" areas and volumes of water, soil and/or crops for testing, 2) Use of risk-based methods to collect samples that are reliably representative of the targeted DU volumes of media of concern, 3) Processing and collection of a subsample (test portion) at the laboratory in a manner that retains the representativeness of the sample submitted, 4) Utilization of Total Oxidizable Precursors (TOPs) processing and Total Organic Fluorine (TOF) analysis of the test portion to identify the full scope of PFAS-related compounds and 5) Quantitative assessment of the data in a manner that focuses on systemic health risk to developing children and women of child bearing age generates a single, cumulative Hazard Index for the mixture of PFAS-related compounds as a whole.

Investigations are initiated by the preparation of well-thought-out, risk-based questions. Example questions include: 1) "Does the makeup and mean concentration of PFASs in the upper 50cm of the subject field indicative of the application of industrial sludges?"; 2) "Does the makeup and mean concentration of PFASs in the upper 50cm of the subject field exceed screening levels for potential adverse uptake into food crops?" and 3) "Does the cumulative risk posed by consumption of food crops cultivated in the subject field exceed an acceptable limit for PFASs?"

Well-thought-out DU areas and volumes of specified media of concern are subsequently designated for sample collection based on factors such as historical records, interviews with farmers and industry representatives, available sample data, observations in the field, current or planned use of areas for cultivation of food crops and consignment orders from purchasers of existing or planned crops. A single, representative sample of media is then prepared for each DU using Multi Increment® collection methods. Examples of risk-based sampling methods include:

- Use of a "compositor" to collection a sample of wastewater over 24-hour or longer period of time;
- Collection and combination of 50 or more "increments" of biosolids from a stockpile proposed for use as a soil amendment;
- Collection and combination of 50 or more "increments" of soil from a targeted field area and depth and
- *In situ* or *ex situ* collection and combination of 50 or more "increments" of a crop cultivated from a field suspected to be impacted by PFASs.

Sample collection methods are "risk-based" in that the objective of the investigation is to assess long-term, chronic health risk associated with continuous exposure to PFASs in the targeted media over many years or uptake of the PFASs into the edible portions of food crops. The use of Multi Increment sampling methods significantly and increases the applicability and reliability of the resulting data and dramatically decreases the number of samples collected and submitted for analysis. Independent, replicate samples (minimum two) are collected from at least 10% of DUs and used to test the precision of the overall sampling and analysis method. Samples are processed and subsampled at the laboratory in a manner that ensures the test portion(s) to be analyzed is representative of the sample provided. Replicate test portions (minimum two) are collected from 10% of the samples submitted in order to test the precision of the sample processing and subsampling method.

Analysis of samples is carried out in a manner that reports complex mixtures of PFASs in terms of three, risk-based groups: 1) "Primary Terminal PFASs" originally present in the samples and identified using methods such as USEPA 537M and 1633 or SGS method MLA110; 2) "Secondary Terminal PFASs" associated with precursor compounds and identified by TOPs processing of the sample prior to analysis and 3) "Excess Fluorine PFASs" associated with additional terminal PFASs present in the sample identified based on a comparison of the concentration of organic fluorine predicted by reported concentrations of Primary and Secondary Terminal PFASs to TOF actually measured by the laboratory.

Data for identified Primary and Secondary Terminal PFASs are compared to risk-based screening levels for the media and exposure pathway of interest and used to generate a cumulative Hazard Index for each group of compounds. Non-targeted analysis suggests that much if not most "excess" organic fluorine identified in samples is associated with unidentified, ultrashort PFAS compounds. As a default, the concentration of excess organic fluorine calculated is conservatively converted into an equivalent concentration of the ultrashort compound perfluoropropanoate ($PFPrA^-$) due to its higher toxicity in comparison to ultrashort compounds such as perfluorethanoate ($PFEtA^-$; aka trifluoroacetate). The resulting concentration is compared to risk-based screening levels for this compound and used to calculate a Hazard Quotient for "Excess Fluorine PFASs." Cumulative or "Total" PFAS risk is subsequently calculated as the sum of the Hazard Indices calculated for Primary Terminal PFASs and Secondary Terminal PFASs and the Hazard Quotient calculated for Excess Fluorine PFASs. A resulting, cumulative Hazard Index greater than "1" indicates a potential risk that requires additional review and action.

The approach described significantly improves the quality of sample data collected reliability of estimates of risk posed by complex mixtures of PFASs. Although focused on PFASs, the concepts and methodologies described are applicable to organic and inorganic contaminants in general. Risk-based sampling methods and comprehensive testing of samples is critical for development of reliable bioaccumulation factors and soil and water screening levels that can ultimately be used to identify high-risk fields or irrigation water prior to the cultivation of crops.

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# From Enrichment to Digestion: Risk–Benefit Evaluation of Selenium-Enriched Foods Under Arsenic Co-Exposure

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**ABSTRACT**

Geological variation in soil selenium (Se) concentrations determines both the nutritional composition and potential toxic element co-occurrence in food crops. In Se-deficient regions, agronomic biofortification, particularly via Se application, has been widely studied to enhance dietary Se intake. Conversely, crops cultivated in seleniferous soils may acquire high Se levels naturally, but this process can also promote the co-accumulation of arsenic (As), a toxic metalloid with partially overlapping uptake pathways. This study evaluated Se and As concentrations, processing losses, and gastrointestinal bioaccessibility in biofortified rice cultivated in Brazil and a range of naturally enriched food products, including polished rice, rice noodles, maize noodles, teas, dried meats, and dietary supplements sourced from seleniferous regions of China. Total elemental concentrations were quantified using inductively coupled plasma mass spectrometry (ICP-MS). Bioaccessibility was assessed using a standardized static in vitro digestion model. Foliar application increased Se concentrations in Brazilian rice between 174 and 9,000 µg/kg, with As concentrations below 1 µg/kg. In contrast, naturally enriched rice showed a broader Se range (76–995 µg/kg) and substantially higher As content (48–321 µg/kg). Cooking retained approximately 35% of Se and reduced As concentrations by 43–71%, depending on the matrix. Based on modelled consumption scenarios, biofortified rice provided between 11% and 433% of the Se recommended dietary allowance (RDA), while naturally enriched cereals contributed 55–62%, supplements up to 161%, dried meats 12%, and teas ≤2%. All Se exposures remained below established tolerable upper intake levels (ULs); however, As exposure from certain naturally enriched rice samples exceeded the European Food Safety Authority (EFSA) chronic benchmark dose, with hazard quotients (HQs) exceeding 3. Se bioaccessibility averaged 24% in cereal products and 49–57% in teas and supplements, while As bioaccessibility ranged from 56% to 80% across all matrices. These results demonstrate that while biofortification via foliar application provide a controlled and low-risk strategy to enhance Se intake, reliance on geogenically enriched foods may pose unintended toxicological risks due to elevated As content and high bioaccessibility. The findings highlight the necessity of integrated nutrient–toxicant assessments when evaluating Se-enrichment strategies, particularly in regions where soil geochemistry contributes to simultaneous exposure to beneficial and harmful elements.

**Keywords:** selenium, arsenic, biofortification, geogenic enrichment, dietary exposure.

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# Effects of Calcination Temperature on the Chemical Properties of Natural and Commercial Diatomites

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**ABSTRACT**

Diatomite is a siliceous, highly porous material increasingly used in soil improvement and environmental applications, although its effectiveness depends strongly on both geological origin and post-treatment modification. This study evaluated three diatomite samples—one commercial product and two natural deposits from northern Thailand collected at depths of 10 m and 15 m—before and after calcination at 600, 800, and 1000 °C for 6 h. All samples were analyzed for pH (1:2 $H_2O$), electrical conductivity ($EC_{1:5}$ $H_2O$), total carbon (TC) by carbon–sulfur analyzer, organic carbon (OC) by the Walkley and Black method, cation-exchange capacity (CEC) using 1 M $NH_4OAc$, and elemental composition (Si, Al, Fe, K, Mg) by X-ray fluorescence (XRF).

Calcination, a simple, rapid, and acid-free modification method, produced clear and systematic changes. $pH_{1:2}$ increased progressively with temperature, rising from 4.72–5.47 in the unheated samples to 6.66–8.24 at 1000 °C, reflecting dehydroxylation and mineral transformation. $EC_{1:5}$ values did not show a consistent decreasing trend after calcination (0.03–0.41 to 0.03–0.38 dS/m). TC and OC were markedly reduced (TC from 3.36–4.05 to 1.51–2.24 g/kg, and OC from 0.99–1.08 to 0.06–0.50 g/kg), confirming efficient removal of organic components. CEC decreased substantially with increasing temperature, particularly at 800 and 1000 °C—from 5.50–27.0 to 3.25–18.5 $cmol_c/kg$—likely due to the loss of exchange sites caused by structural collapse, sintering, and the reduction of surface functional groups during high-temperature treatment (El Ouardi et al., 2020). Si increased noticeably after calcination (from 64.6–73.0 to 74.2–77.4%), while Al showed a slight increase (10.5–13.9 to 11.5–16.8%). Fe decreased sharply across all temperatures (4.98–18.8 to 2.11–10.1%), and K exhibited a similar decline (2.73–5.73 to 1.30–2.81%). Mg varied only slightly among samples (0.71–0.93 to 0.78–0.90%), reflecting source-dependent mineral differences and thermal-stability contrasts.

Overall, calcination markedly altered the chemical properties of both commercial and natural diatomite, increasing pH and modifying elemental composition while reducing TC, OC, and CEC. To optimize its applicability in soil and environmental systems, further work should investigate specific surface area, mineralogical transformations, and sorption behavior, as well as evaluate shorter holding times at high temperatures to minimize structural degradation while preserving functional performance.

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# Soil Cadmium Immobilization and Selenium Activation: A Strategy to Enhance Health in High Geological Background Areas

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**ABSTRACT**

High geological background areas are frequently characterized by the coexistence of cadmium (Cd) contamination and selenium (Se) deficiency, which poses substantial threats to food safety and human health. This study integrated multiple technical approaches and risk assessment methodologies to clarify the pivotal role of soil Cd immobilization and Se activation in enhancing regional health levels. From the technical perspective, hydroxyapatite-modified biochar (PBC) derived from Se-enriched straw enhanced soil available Se through synergistic mechanisms including intrinsic Se release, adsorption suppression, and soil Se activation. This treatment increased grain Se content by 55.6% and achieved a net benefit of US$18,301 per hectare. Meanwhile, the alkalizing bacterium *Stenotrophomonas* sp. H225 (SH225) reduced Cd accumulation in edible tissues by 44.7% and increased Se accumulation by nearly 4-fold by secreting piperidine to elevate rhizosphere pH and generating hydrogen sulfide for Cd precipitation. In terms of risk assessment, a novel benefit-risk-value (BRV) criterion was established. Combined with bioaccessibility analysis, the results revealed that traditional single-element assessment overestimated Cd-related health risks, while obvious Se deficiency was identified in adults and the elderly. Collectively, the Cd immobilization and Se activation technologies can simultaneously address Cd contamination and Se deficiency issues, providing technical support and assessment basis for improving health levels in high geological background areas.

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# Arbuscular mycorrhizal fungi suffer from perfluorooctanoic acid in soil but ameliorate negative effects on plant performance

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**ABSTRACT**

*Per*- and polyfluoroalkyl substances (PFAS) can impact plant growth, while how the symbiosis of arbuscular mycorrhizal fungi (AMF) would affect the response of plant performance to PFAS contamination remains entirely unknown. To address this gap, we conducted an eight-week pot experiment to investigate the function of AMF in plant response to perfluorooctanoic acid (PFOA) using spring onion (*Allium cepa*) as phytometer. At harvest, we measured whole-plant performance (including growth, root morphology and mycorrhizal association) and soil parameters (pH and litter decomposition rate) as affected by PFOA and AMF inoculation. Our results showed that PFOA reduced the AMF colonization rate, frequency of arbuscules and vesicles. It also negatively affected root traits including root biomass, total length, average diameter, and root tissue density, while positively affecting specific root length and surface area. Moreover, PFOA significantly decreased leaf biomass, maximum height, and total biomass, but did not affect root/shoot ratio, soil pH, and litter decomposition. The inoculation of AMF reduced the negative effect of PFOA on root diameter and the positive effects on specific root length and surface area. It also increased the total root length, but this effect was neutralized by PFOA. Our results suggest that AMF inoculation alters the resource allocation strategies of plants under PFOA stress, favoring shoot growth at the expense of roots. This study provides evidence that AMF inoculation enhances plant resistance to environmental stressors and highlights the need to explore its interactions with plants and pollutants like PFAS.

**Keywords:** Perfluorooctanoic acid (PFOA); Arbuscular mycorrhizal fungi (AMF); Root traits; Plant-soil system; Plant resistance

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# Engineering Iron–Microbe Interfaces on Biochar to Regulate Phosphate Fixation and Ibuprofen Retention across Soil–Water Continua

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## ABSTRACT

Biochar is a carbon material that can be produced from renewable biomass and has been primarily used in soil remediation and regarded as a functional carbon material due to its cost-effective and environmentally friendly characteristics. Aside from the primary aim of pollution remediation, biochar in this study was prepared using the invasive plant *Leucaena leucocephala* to achieve the forest conservation goal. Biochar was sequentially modified by acid washing followed by iron loading. The textural properties were enhanced, raising the BET surface area from 68 to 102 $m^2/g$ and improving pore volume 266%. Magnetically iron-modified biochar (Fe-ATB) achieved efficient phosphate recovery, exhibiting a 17-fold increase in binding affinity over pristine biochar. Magnetite formation (~ 31% Fe oxide) enabled high magnetic recovery efficiencies in both aqueous (96.0%) and soil (91.2%) systems, supporting its economic viability for reusable adsorption cycles. Looking at the promising potential of Fe-ATB for pollution remediation, further research will be conducted on an emerging contaminant, Ibuprofen (IBP), where additional modification of microbe loading will be applied to the biochar. Out of 27 bacterial strains tested, six strains including *Cellulosimicrobium funkei, Promicromonospora thailandica, Serratia marcescens, Bacillus aryabhattai, Sphingorhabdus buctiana, and Gordonia terrae* showed high IBP tolerance up to 500 mg $kg^{-1}$. Therefore, applying iron-modified and microbe-loaded biochar is expected to improve IBP degradation, adsorption, and removal, as well as facilitate magnetic separation and circular utilization.

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# Occurrence and Transformation of Selenium and Cadmium in Porewater During Flood and Drainage: Implications for Safe Production of Rice in Cadmium-Contaminated Seleniferous Paddy Soils

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**ABSTRACT**

Simultaneously improving micronutrient nutrition and minimizing toxic metal exposure from rice is a global food-safety challenge in many monsoon influenced or geogenically enriched agricultural regions, where naturally seleniferous paddy targeted for Se biofortification often co-occur with cadmium (Cd) contamination. Here, we conducted a multi-site field investigation in Guangxi, China, sampling soils and porewater across four cultivation stages (July, August, September, and December 2024) spanning alternating flooded and drained conditions. Porewater chemistry was characterized alongside size-resolved Se and Cd partitioning (ionic and colloidal) using asymmetric flow field-flow fractionation (AF4) coupled with ICP-MS/TOC analysis, Se speciation by HPLC-ICP-MS, organic matter characterization by FT-ICR-MS, and particle-scale imaging by TEM/STEM-EDS. Across flood-drainage transitions, both Se and Cd shifted systematically between ionic and colloid-associated pools: flooding decreased ionic Se from 78.5% to 55.2% while increasing mineral-sized colloidal Se (130 kDa-150 nm) from 0% to 42.8%, and decreased ionic Cd from 94.5% to 54.3% while increasing small colloidal Cd (1-40 kDa) from 22.3% to 35.5%. Critically, direct Se-Cd immobilization via CdSe was not supported: CdS signals were consistently detected whereas CdSe was absent, indicating that Se and Cd are not controlled by a single coupled precipitation pathway in paddy. Mechanistically, Cd speciation was dominated by ionic Cd during drainage and by labile complexes with low molecular weight protein-like colloids during flooding, consistent with oxidative weakening of protein binding and release of ionic Cd during the drainage stage. In contrast to the common assumption of inorganic Se dominance in seleniferous soils, porewater Se was overwhelmingly dominated by L-Se-methylselenocysteine, peaking at 75.3% during flooding and decreasing to 55.2% during drainage, when minor but more plant available selenite (20.1%) and selenate (14.1%) emerged during drainage. These findings identify drainage as a critical window where Se activation and heightened ionic Cd risk co-occur, providing a mechanistic basis for water-management optimization and targeted amendments to reconcile Se biofortification with Cd-safe rice production.

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# Selenium-Based Rapid Health Risk Diagnosis and Green Remediation of Heavy Metal Pollution

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## ABSTRACT

Heavy metal (HMs) contamination has emerged as a global environmental challenge threatening farmland ecological security and agricultural product quality. In regions characterized by high geochemical background levels in combination with intensive anthropogenic activities, toxic metals such as mercury (Hg), cadmium (Cd), and arsenic (As) tend to accumulate continuously along the soil–crop–human continuum, thereby substantially increasing dietary exposure and associated health risks. Mitigating HMs contamination while maintaining agricultural productivity and nutritional security remains a critical challenge for farmland remediation and risk management.

To address the major challenges of unclear health risks, poorly understood process mechanisms, and the lack of green remediation technologies associated with soil HMs pollution in China, this study systematically elucidates the key regulatory roles of selenium (Se) in environments co-contaminated with Hg, Cd, and As. The results demonstrate that Se effectively suppresses the migration, transformation, and bioaccumulation of HMs in soil–crop systems through multiple pathways, including complexation and precipitation, enhancement of antioxidant defenses, regulation of metal-related gene expression, and maintenance of nutritional homeostasis. On this basis, a dual-regulation concept termed “Se enhancement for pollution mitigation” was proposed, and an integrated remediation framework incorporating microbe–plant interactions, agronomic management, and functional materials was established. This framework successfully achieved the synergistic reduction of HMs risks and enhancement of Se nutrition in rice cultivated in typical high-geochemical-background regions, such as Tongren, known as the "Hg Capital of the China". Furthermore, from the perspective of human health risk management, a novel Benefit–Risk Value (BRV) assessment method based on Se-HMs antagonistic interactions was developed. This method overcomes the limitations of conventional risk assessment frameworks that focus exclusively on metal toxicity while neglecting the protective nutritional role of Se, enabling an integrated evaluation of food safety and nutritional benefits.

Collectively, these outcomes have led to the development of a suite of remediation technologies and soil conditioners, and to the establishment of the “Tongren model” for risk control and safe utilization, providing scientific evidence and technical support for the sustainable management and green remediation of farmland contaminated by HMs in high geochemical background regions.

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# In Situ Removal of Heavy Metals from Farmland Using Lignin Hydrogel-Based Nanocomposites: A Sustainable Strategy for Simultaneous Crop Production and Soil Remediation

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## ABSTRACT

Heavy metal contamination in farmland poses a critical threat to global food security, particularly in densely populated regions of East Asia where arable land is scarce. Conventional remediation techniques (e.g., chemical immobilization, phytoremediation) often fail to achieve complete metal removal or disrupt agricultural production, making them unsuitable for areas requiring continuous land use. To address this challenge, we developed a series of lignin hydrogel-loaded nanoparticle composites enabling in-situ metal removal while maintaining crop cultivation. We synthesized multiple nanocomposites by embedding nanoparticles (e.g., FeS, $Fe_3O_4$, $Fe_2O_3$) into a lignin-based hydrogel network, whose three-dimensional porous structure ensures high loading capacity and uniform dispersion of nanoparticles, preventing aggregation and enhancing reactivity. Among these, the FeS-loaded lignin hydrogel (FeS@LH) demonstrated exceptional performance, with a maximum cadmium (Cd) adsorption capacity of 833.3 mg/g via chemical precipitation (CdS formation) and ion exchange. Recently, we optimized the synthesis process using a one-pot method to produce $Fe_3O_4$@LH and $Fe_2O_3$@LH, simplifying preparation and reducing costs for scalable application. Field trials validated the efficacy of FeS@LH under real farming conditions: in a water spinach plot, application of FeS@LH (30 g/m²) for 30 days reduced bioavailable soil Cd by 37.6% and vegetable Cd by 34.5%; in a rice paddy system, a single application reduced soil Cd by 0.42–31.72% and grain Cd by 1.52–49.11% after 94–103 days, and continuous remediation over multiple seasons showed sustained Cd reduction without compromising yield. The composite also improved soil quality (total nitrogen increased by 16.1%; organic matter increased by 13.8%) and exhibited high biosafety (zebrafish survival rate >98%) and recoverability (>88%). This study demonstrates that lignin hydrogel nanocomposites achieve efficient heavy metal removal through synergistic synthesis optimization, interface behavior control, and field-scale validation, offering a sustainable "remediation-while-farming" solution for contaminated farmland in land-stressed regions, which aligns with the conference's focus on innovative soil composites for environmental applications.

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# Spatial Differentiation Pattern and Driving Mechanisms of Co-enrichment of Selenium and Cadmium in Soils from a Typical Indigenous Zinc Smelting Area

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**ABSTRACT**

Selenium (Se) is an essential trace element for both plants and humans. It often exhibits a co-enrichment characteristic with the toxic element cadmium (Cd) in soil, and this phenomenon is particularly pronounced in karst areas with the superposition of high geological background values and mining-smelting activities. At present, systematic research on the distribution patterns and driving mechanisms of soil Se and Cd co-enrichment remains relatively scarce. In this study, a total of 1,528 topsoil samples were systematically collected from a typical area with the superposition of high geological background values and historical indigenous zinc smelting activities in Southwest China. Combined with multivariate statistical analysis, geostatistical methods and random forest models, the spatial distribution patterns and co-enrichment driving factors of Se and Cd in the soil were investigated. The results showed that the soil Se content in the study area ranged from 0.09 to 1.79 mg/kg, with a mean value of 0.65 mg/kg, which was significantly higher than the soil Se background values of the world and China. In contrast, the soil Cd content exhibited a wide variation range of 0.38 to 15.10 mg/kg and a mean value of 4.22 mg/kg. In terms of spatial distribution, the high-value areas of Se and Cd co-enrichment are concentrated in the northern pastureland region as well as the central region characterized by the superposition of carbonate rocks and historical indigenous zinc smelting activities. Results from correlation analysis and random forest models showed that soil organic matter (SOM), lithological distribution (LIT), distance to mining-smelting sites (DTM), and soil nitrogen (N) content were the core driving factors regulating the spatial distribution of Se and Cd in the study area. Furthermore, bivariate local Moran's I was employed to construct a spatial correlation model between Se and Cd enrichment characteristics and key driving factors, thus identifying the dominant factors affecting the enrichment and distribution of Se and Cd in different enrichment areas: In the central region, the weathering of carbonate rocks combined with the exogenous input from indigenous zinc smelting activities has jointly intensified the co-enrichment of Se and Cd. In the northern pastureland region, high contents of SOM and N are important factors controlling the enrichment and distribution of Se and Cd. In conclusion, mining-smelting activities and land use changes are important factors affecting the synergistic enrichment and spatial differentiation pattern of Se and Cd in regional soils. This study reveals the multi-factor driving mechanism of Se and Cd co-enrichment in the compound-impacted area, which can provide theoretical support and practical guidance for the rational development of Se-rich soil resources as well as the precise prevention, control and remediation of Cd pollution.

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# Cell-level Toxicological and Biodegradation Responses of Pure Bacterial Cultures to Per- and Polyfluoroalkyl Substances (PFAS)

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFAS), characterized by strong carbon–fluorine (C–F) bonds, have been widely recognized as "almost forever chemicals" due to their extreme persistence and pronounced toxicity to microorganisms. Despite increasing concern regarding their environmental accumulation, the quantitative impacts of structurally diverse PFAS on bacterial growth, viability, and pollutant degradation at the cellular level remain poorly understood. In this study, we systematically investigated the growth, survival, and degradation responses of pure bacterial cultures exposed to representative PFAS, including perfluorobutanoic acid (PFBA), perfluorooctanoic acid (PFOA), and 6:2 fluorotelomer alcohol (6:2-FTOH). *Escherichia coli* K-12 BD792 was employed as a non-degrading control, while four known aerobic PFAS-degrading isolates (*Pseudomonas aeruginosa* Migula 1900, *Pseudomonas fluorescens* DSM 50090, *Delftia acidovorans* DSM 39, and *Rhodococcus jostii* DSM 44719) were selected to evaluate degradation-associated toxicity. In addition, two toluene-degrading isolates (*Pseudomonas putida* F1, *Burkholderia cepacia* G4), and one biphenyl-degrading isolate *Burkholderia xenovorans* LB400 were included to assess the potential interference of PFAS with the biodegradation of co-occurring organic pollutants. Across a total of eight bacterial isolates, growth kinetics, resting-cell viability, and PFOA degradation rates were quantitatively examined under PFAS exposure. PFAS attenuation was monitored using liquid chromatography–mass spectrometry (LC–MS), while fluoride release, as direct evidence of defluorination, was determined by ion chromatography and a fluoride ion-selective electrode. Furthermore, flow cytometry was applied to examine cell-to-cell heterogeneity in a pure culture, including changes in cell size, cellular complexity, and live/dead cell ratios. The results provide insight into cell-level responses to a toxicant, which may differ from population-level averaged observations, and implications for the applicability of single-cell sorting of PFAS-degrading and/or PFAS-tolerant bacterial cells in accelerating selective enrichment of PFAS-degrading microbes.

**Acknowledgments**

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# Selenium Dynamics in Seleniferous Soils of Punjab: Role of Organic and Inorganic Amendments in Mitigating Selenium Toxicity

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**ABSTRACT**

Selenium (Se) is a trace element with a narrow threshold between essentiality and toxicity in ecological and agricultural systems, particularly in seleniferous soils of northwestern India. This study evaluated the effects of organic (biochar, farmyard manure [FYM], crop residue straw) and inorganic (gypsum) amendments on selenium fractionation and speciation in seleniferous soils. Laboratory experiments were conducted with graded amendment levels. Soil pH, electrical conductivity (EC), organic carbon (OC), total and available Se, Se fractions (water-soluble, exchangeable, organic-bound, residual), and Se species [selenite (Se(IV)), selenate (Se(VI)), selenide (Se(-II)), elemental Se (Se(0))] were quantified. Results showed that organic amendments significantly shifted selenium from more labile forms (water-soluble and exchangeable) toward less mobile organic-bound and residual fractions, indicating enhanced Se immobilization. This effect was attributed to increased microbial activity and organic matter interactions that drive reduction and complexation processes, consistent with recent observations that soil microbial communities and dissolved organic carbon regulate Se bioavailability under organic amendment regimes (Zhang et al., 2022). Biochar influenced Se speciation by altering soil redox conditions and organo-mineral interactions, reducing available Se, in line with mechanistic insights into biochar–Se interactions (Yao et al., 2020). Inorganic gypsum affected soil chemical properties, moderately reducing soluble Se forms through ionic interactions (Etteieb et al., 2024). Collectively, amendment-induced changes in Se fractionation and speciation reduced its mobility and potential toxicity, demonstrating that integrated use of organic and inorganic amendments can sustainably manage selenium-rich soils by regulating Se transformations and minimizing environmental risk.

**Keywords:** Selenium speciation; Selenium fractionation; Seleniferous soils; Organic and inorganic amendments; Selenium immobilization

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# The potential role of groundwater microplastics on arsenic cycling in alluvial aquifers: insights from links of DOM characteristics and microbial community

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**ABSTRACT**

Microplastics (MPs) in groundwater exhibit complex surface properties and generate MP-derived dissolved organic matter (MP-DOM), which exerts a strong regulatory effect on elemental cycling within aquifers. DOM can alter the metabolic activities of microbial communities, thereby enhancing microbially mediated arsenic (As) biogeochemical processes. However, the influence of MPs and MP-DOM on the migration and transformation of As in alluvial aquifers remains poorly understood to date. To address this knowledge gap, we selected high-As alluvial aquifer systems in the middle reaches of the Yangtze River basins and used Fluorescence excitation-emission matrices (EEMs) spectra, Ultra high-resolution Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS), 16S rRNA and groundwater chemistry to reveal the potential cycling behavior of As in alluvial aquifers under MPs-containing groundwater conditions. Results indicated severe As pollution (14.05-240.03 μg/L) in confined groundwater (CG) with relatively lower MPs values. By contrast, significantly higher MPs concentrations (3940 to 17130 items/m³) with lower As values (0.27-11.19 μg/L) were detected in unconfined groundwater (UG). EEMs and FT-ICR-MS analysis revealed abundant lignins and specific molecular formulas with higher H/C ratios (>1.5) and lower O/C ratios (<0.50), which are the distinctive traits of MP-DOM. This unique MP-DOM can sequester As through the formation of As-Fe-DOM ternary complexes. Hydrogen bond interaction and/or surface complexation serve as another important way for arsenic immobilization by MPs. Moreover, the ultimately higher diversity and abundance of bacteria with As tolerance and As metabolic capabilities (e.g., *Methylomonas*, *Azospira* and *Acinetobacter*) in CG likely drive the reductive dissolution of Fe(III) oxides/oxyhydroxides, consequently promoting the release of As adsorbed onto these minerals, with MP-DOM serving as electron donors. This research provides new insights into the roles of MPs and MP-DOM in regulating the mobilization and enrichment of As in alluvial aquifers, thereby advancing our understanding of the genesis of geogenic As-contaminated alluvial aquifer systems.

**Keywords:** High-Arsenic Groundwater, Microplastics, Biogeochemistry, Dissolved Organic Matter, FT-ICR MS

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# Recent Strategies in Cadmium Translocation Control in Rice Plants: Mechanisms and Integrated Model

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## ABSTRACT

Cadmium (Cd) contamination in paddy soils severely threatens food security and human health. Globally, 14%-17% of arable land (242 million hectares) is contaminated by toxic heavy metals, with China's farmland soil showing a 7% Cd over-standard rate. Zhejiang Province faces a more severe challenge with a 15.6% over-standard rate (≈1.38 million mu). As rice is the staple food for over half of China's population, with ~10% of grains exceeding Cd limits, this study develops efficient Cd control technologies aligned with the national strategy of "Putting People's Life and Health First".

Three core technical directions were explored: arbuscular mycorrhizal fungi (AMF)-rice symbiosis, calcium (Ca)-based amendments, and rice-Sesbania cannabina intercropping. For AMF symbiosis, Glomus etunicatum was applied in seedling trays, achieving a 30% colonization rate without affecting rice growth and reducing Cd absorption by over 50%. AMF alleviated Cd-induced cell damage, enhanced photosynthetic performance, reduced Cd flow velocity in root xylem by ~50%, and regulated key transporter genes (e.g., NRAMP1 upregulated by 2.9-fold, ABCG48 by 4.7-fold). Validation with OsNRAMP5-deficient mutants confirmed AMF's role in inhibiting Cd translocation to grains.

Regarding Ca-based amendments, lime (CaO, $Ca(OH)_2$, $CaCO_3$) was selected for its low cost and effectiveness. In alkaline coastal fluvo-aquic soil (pH=8.17, Ca=0.36%), $CaCO_3$performed best by continuously releasing $Ca^{2+}$, increasing soil pH and Ca concentration, and reducing Cd bioavailability. When the Ca/Cd ratio reached 20, Cd adsorption on rice root iron plaque decreased by ~70%. High-throughput sequencing showed $CaCO_3$ altered soil bacterial community structure, reducing richness by ~4 times.

In the rice-Sesbania cannabina intercropping system (1 row Sesbania + 5 rows rice, 25cm spacing), field and pot experiments demonstrated a ~50% reduction in grain Cd content. Sesbania's superior biomass promoted rice root growth and iron plaque formation; when plaque thickness exceeded 15-25 mg/kg, Cd migration to roots was inhibited. Additionally, Sesbania's shading reduced rice transpiration rate by 25% during the booting stage, suppressing Cd transport to grains with only a 10% yield reduction.

Based on these findings, an integrated "One Mixing, Two Applications, Three Intercroppings" model was established: mixing AMF inoculant with substrate (0.5% volume), applying $CaCO_3$ (200-300 kg/mu), and intercropping rice with Sesbania (5:1 row ratio). This model integrates biological, chemical, and agronomic measures, enabling safe rice production in Cd-contaminated soils and providing a practical solution for "production-while-repair".



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# PFAS Composition in Irrigation Water Dictates PFAS Uptake by Lettuce: Evidenced by Field Sampling and Laboratory Simulation

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFAS) have attracted increasing global concern owing to their extreme environmental persistence, bioaccumulative potential, and associated human health risks. Landfills are recognized as major point sources of PFAS release, particularly in rapidly urbanizing regions where many landfills are located in close proximity to agricultural land. This spatial configuration creates a direct exposure pathway linking "landfill–water–soil–crop–human," thereby elevating the potential for agricultural and dietary risks. Following international restrictions on legacy long-chain PFAS such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), industrial production has progressively shifted toward short-chain homologues and fluoroether-based alternatives.This transition, however, introduces a dual and underappreciated environmental challenge. On the one hand, many emerging PFAS alternatives exhibit higher aqueous solubility and mobility, facilitating their migration through landfill liners and vadose zones and enhancing their transport along groundwater–soil continua into crop root zones. On the other hand, their widespread introduction has substantially reshaped the compositional profiles of PFAS in surrounding environments. When these emerging compounds coexist with legacy long- and short-chain PFAS in complex mixtures, their bioavailability, competitive interactions, and influence on the environmental behavior of existing PFAS remain poorly understood. Such complexity challenges conventional assessment frameworks, thereby contributing to delays and inadequacies in current agricultural environmental regulations.

To address these knowledge gaps, this study investigated an agricultural system surrounding three representative landfill in southern China. By integrating field surveys with laboratory-based interaction simulations, we systematically characterized the occurrence of PFAS in farmland irrigation water and elucidated differential root accumulation behaviors under multi-PFAS coexistence conditions.Field investigations revealed widespread mixed PFAS contamination with pronounced spatial heterogeneity. Irrigation water adjacent to simple landfills exhibited a composite pollution profile dominated by the fluoroether substitute GenX (1005.94 ±398.37 ng/L), accompanied by elevated concentrations of short-chain PFAS (e.g., PFBA and PFBS) and detectable residues of long-chain compounds. In contrast, areas influenced by properly managed sanitary landfills showed markedly reduced GenX levels but comparatively higher residual concentrations of legacy PFAS. This clear divergence in compositional profiles indicates that crop roots in different regions are subjected to fundamentally distinct PFAS stress environments, characterized by chemically crowded mixtures encompassing diverse chain lengths and functional groups.

To further evaluate how PFAS composition regulates bioavailability, root accumulation behaviors were compared under single-compound and mixed-exposure conditions. The results demonstrated that, in mixed systems, the accumulation of most legacy perfluoroalkyl acids was significantly inhibited. This suppression exhibited strong structure dependence: with increasing carbon chain length and molecular volume, competitive disadvantage became increasingly pronounced (e.g., PFNA accumulation decreased by 49%, whereas PFBA decreased by only 13%). In contrast, GenX accumulation was largely unaffected by coexisting PFAS, despite sharing a fluorinated backbone with legacy compounds. This distinctive behavior suggests that the incorporation of an ether linkage may enable GenX to access root tissues via alternative uptake pathways—such as nonspecific diffusion or independent carrier-mediated transport—thereby circumventing the competitive inhibition observed among conventional PFAAs.

In summary, this study underscores the urgency of incorporating emerging alternatives and interactions between PFAS compounds for plant uptake into the prediction of soil-plant transfer and human health risk assessment of vegetable fields receiving PFAS-contaminated irrigation water.

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# Removal Performance and Mechanism of MOF-Based Iron-Carbon Composite Materials for PFOA and PFOS Electron Transfer Mediated by Iron Sites

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**ABSTRACT**

This study developed a metal–organic-framework-derived iron–carbon composite (Fe-NC-0.1) for the efficient removal of mixed PFOA/PFOS contamination from water. Using ZIF-8 as the structural template and FePc as the iron source, iron–carbon materials with tunable pore structures and active sites were synthesized through a solution-based reaction followed by pyrolysis. Among the materials with different Fe loadings, Fe-NC-0.1 retained a well-defined polyhedral morphology, exhibited the largest specific surface area (561.56 m2/g), and contained abundant single-atom Fe sites. Batch adsorption experiments demonstrated that Fe-NC-0.1 rapidly removed PFOA and PFOS, achieving 90% removal within 2 min in single-PFOA/PFOS systems and maintaining high performance under mixed PFOA/PFOS contamination. Fe-NC-0.1 showed strong resistance to interference across a wide pH range (3-11) and in the presence of common groundwater ions. Compared with commercial activated carbon, Fe-NC-0.1 exhibited faster adsorption and higher efficiency at low dosage and maintained >99% removal efficiency over five regeneration cycles.

The adsorption mechanism involves electron transfer and hydrophobic interactions, in which adsorption is primarily governed by the interaction between the PFAS tail functional groups and the Fe–N coordination sites, accompanied by electron transfer from the single-atom Fe to the central functional groups of PFOA/PFOS. XPS, FT-IR, Raman spectroscopy, and DFT calculations all confirmed Fe-centered chemisorption, with stronger affinity toward PFOS than PFOA, consistent with the experimental observations. Dynamic column experiments further validated effective removal under flow conditions. Overall, Fe-NC-0.1 integrates high adsorption capacity, rapid kinetics, regenerability, and magnetic recoverability, demonstrating strong potential for PFAS remediation in groundwater treatment systems.

# Remediation of oxytetracycline-contaminated calcareous soil by a novel Zinc oxide/Schwertmannite composite: interface behavior and plant synergy

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## ABSTRACT

**Introduction:** The land application of livestock manure exacerbates the accumulation and migration risks of oxytetracycline in calcareous soils of northern China. The characteristics of such soils—high pH, high calcium, and low organic matter—not only severely restrict the soil's intrinsic immobilization capacity but also render sole phytoremediation inefficient. To address this dual challenge, this study developed a novel composite, Zinc oxide/Schwertmannite composite, aiming to construct an efficient "material-assisted phytoextraction" synergistic remediation strategy.

**Methodology & Results:** Zinc oxide/Schwertmannite composite was synthesized via biosynthesis and co-precipitation[1-2]. Adsorption tests in aqueous systems demonstrated that the material possesses excellent adsorption performance (35.98 mg/g) and solar photocatalytic potential. Through 56-day soil incubation and pot experiments, it was found that Zinc oxide/Schwertmannite composite acts as a "dynamic reservoir" in the soil, actively competing to immobilize oxytetracycline, effectively buffering phytotoxicity, and creating an enrichment interface for plant extraction. Zinc oxide/Schwertmannite composite not only increased the biomass of *Sedum plumbizincicola* but also optimized the rhizosphere microenvironment, enhancing the oxytetracycline extraction efficiency of the plant by 4.71 times, thereby achieving high-efficiency removal via "material immobilization–plant extraction". Meanwhile, the recovery of inhibited soil catalase activity confirmed the restoration of metabolic functions.

**Conclusion**: This study confirms that, targeting the migration risk of oxytetracycline in alkaline soils, the synergy between Zinc oxide/Schwertmannite composite and the hyperaccumulator successfully couples the "immobilization" and "extraction" processes. This "detoxification-enhancement" strategy offers an innovative and green solution for managing antibiotic contamination in agricultural soils with similar properties.

**Keywords:** Zinc oxide/Schwertmannite composite; oxytetracycline; interface behavior; calcareous soil; phytoremediation

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# Digital Mapping for Spatial Prediction of Soil Properties Using Machine Learning Models for Soil Management in Rice Cultivation Areas Affected by Salt: A Case Study of Muang Phia, Ban Phai, Khon Kaen

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**ABSTRACT**

Salt-affected soils in Northeast Thailand represent a major constraint to rice production. Spatial information on soil properties is essential for effective soil and fertilizer management. This study aimed to develop digital maps predicting the spatial distribution of organic matter (OM), available phosphorus (P), and available potassium (K) using Quantile Random Forest (QRF) models and to analyze relationships among OM, P, K and salinity levels to provide soil management recommendations for rice cultivation in Muang Phia subdistrict, Ban Phai district, Khon Kaen province, covering 35,255 rai (approximately 5,640 hectares). Data from 107 soil samples collected at a 0–30 cm depth were combined with remote sensing indices and environmental covariates derived from Landsat 9 OLI imagery, NASA SRTM digital elevation model, and existing soil, geological, and land use maps. Results showed that key variables influencing OM and K were spectral reflectance indices and salinity indices, while P was primarily influenced by topography and geology. The QRF algorithm achieved satisfactory prediction performance with Nash-Sutcliffe efficiency (NSE) values of 0.66 for OM, 0.47 for P, and 0.63 for K. Based on the OM, P, and K maps, the study area was classified into 7 soil and fertilizer management zones for rice cultivation, with the zone having low levels of all three nutrients (L-L-L) being the most predominant (42.86%). The resulting maps can support site-specific soil and fertilizer management planning, thereby reducing production costs and improving rice productivity in salt-affected areas sustainably.

**Keywords:** digital soil mapping; machine learning; plant nutrients; salt-affected soils; soil management

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# Removal Mechanism and Process Application of Soil Washing Technology for Heavy Metals and Salt Ions in Contaminated Soil

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**ABSTRACT**

Heavy metals and excessive inorganic salts in soil can degrade soil physicochemical properties, reduce soil quality, and result in human health risks.Currently, most conventional soil washing equipment adopts mineral processing production line configurations, which suffer from several limitations: lengthy processing lines, narrow applicability (restricted to sandy soils only), prolonged installation cycles, high water consumption, and substantial energy consumption.

To address the need for efficient remediation of diverse contaminated soil types, particularly clayey soils, it is essential to thoroughly investigate the occurrence forms and migration/transformation mechanisms of heavy metals and inorganic salt ions in clayey soils. Simultaneously, soil remediation equipment must be updated and optimized to enhance the removal efficiency of heavy metal ions and salt ions, thereby achieving the sustainable remediation objectives of water and energy conservation.

The soil washing equipment developed in this study adopts a modular integrated design, dividing the entire contaminated soil treatment process into five sequential stages: (1) feed pretreatment, (2) scrubbing and screening, (3) efficient classification and concentration, (4) sludge pressure filtration, and (5) water circulation treatment and reuse. This design establishes a complete closed-loop water circulation system. The equipment offers several advantages: convenient transportation, significantly shortened installation and commissioning cycle (reduced from 1–2 months for conventional equipment to less than 10 days), and high degree of automation enabling linked operation across modules, which effectively minimizes manual intervention and ensures continuous and stable operation.

Furthermore, by incorporating key technologies such as cylindrical scrubbers equipped with wear-resistant liners and high-efficiency deep cone thickeners with overflow functionality, the equipment can effectively achieve synergistic reduction, hazard elimination, and resource utilization of various contaminated soil types, including clayey soils..

**Key words:** Soil Remediation, Heavy Metals, Excessive Inorganic Salts, Clayey Soil, occurrence forms, Soil washing equipment,Modular Integrated Design.

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# Effects of Organic Materials on Nitrification Process in Saline-Alkali Farmland Soil

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## ABSTRACT

In order to address the issues such as the deteriorating ecological environment, low water and fertilizer use efficiency, and intensified non-point source pollution in salinized farmlands along the Yellow River, this study investigated the effects of organic materials on soil nitrification in saline-alkali cropland. Experimental treatments included combined application of organic materials (corn straw (C1), biochar (B1)) and nitrogen fertilizer at three levels (N0, N, N2), with no organic material and no nitrogen fertilizer as the control (B0N0, C0N0). The results showed that compared with C0N0, the C1N0 treatment generally alleviated nitrogen mineralization and nitrification processes in saline soil, whereas the C1N2 treatment increased the nitrogen mineralization rate and nitrification rate in saline soil. Straw returning and reduced nitrogen fertilizer application can retain more ammonium nitrogen, thereby inhibiting nitrification of soil nitrogen, reducing the environmental pollution risk of nitrate leaching, and mitigating soil nitrogen loss in saline soils. In addition, corn straw and biochar treatments increased the relative abundance of Actinobacteriota, Bacteroidota and Firmicutes in the soil, while decreasing the relative abundance of Gemmatimonadota, Chloroflexi, Acidobacteria, Planctomycetes and Patescibacteria. Biochar significantly altered the fungal community structure in moderately saline soil, and the addition of corn straw significantly increased beneficial fungal groups in moderately saline soil. Ammonium nitrogen, nitrate nitrogen and nitrate reductase were the main environmental factors affecting the bacterial community in moderately saline soil. Ammonium nitrogen and nitrate reductase mainly influenced the bacterial community, and nitrate nitrogen also predominantly affected the bacterial community. Soil nitrate reductase and ammonium nitrogen were the dominant environmental factors shaping the fungal community in moderately saline soil, followed by nitrate nitrogen, electrical conductivity and nitrite reductase. The results of this study provide a theoretical basis for establishing a reasonable and efficient regulation model of organic materials in salinized farmlands, improving nitrogen uptake and utilization efficiency as well as soil nitrogen transformation capacity. They are also of great significance for guiding the formulation of efficient nitrogen fertilizer management strategies for salinized land and reducing environmental pollution caused by nitrogen loss.

**Keywords: Saline soil; Organic materials; Soil nitrogen transformation; microbial community**

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# "Reshaping soil structure": A systems engineering mode for ecological management of Salt-Affected Land

**Shuwen Hu**

**ABSTRACT**

Confronting the central challenge in reclaiming salt-affected soils, namely structural degradation that suppresses water infiltration and leaching efficiency, this work presents a ecological framework that prioritizes rebuilding soil aggregate structure to catalyze efficient desalinization. A series of bio-based amendments was innovated to accelerate micro-aggregation and enlarge capillary porosity, increasing leaching efficacy five- to thirteen-fold. In parallel, salt-tolerant controlled-release fertilizers were devised to modulate rhizosphere nutrient delivery and optimize crop habitat. Hydraulic interventions, including gated embankments and groundwater regulation, sever salt-return pathways. The integrated mode thus orchestrates structure reconstruction, high-efficiency desalinization, microbial community rehabilitation, nutrient cycling, and ecological restoration. Tailored for the arid region, a pioneering water-soluble amendment combined with functional fertilizers enables a unified regime of drip irrigation, fertilization, and soil improvement, reducing costs by 80 percent relative to conventional practices. Over a decade of validation across five representative saline and sodic landscapes and deployment in 28 counties of 11 provinces has reclaimed 1.95 million mu of saline farmland, markedly boosting yields and generating 17.6 billion yuan in economic benefit. The paradigm offers a replicable, systems-level solution for converting salt-impaired soils into productive and resilient agroecosystems.

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# Reclamation of saline-alkali soils using fulvic acid: mechanisms and field effects

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**ABSTRACT**

Fulvic acid is one of organic soil amendments used to ameliorate saline-alkali soils and to alleviate the negative effects of salt-affected soils on crops. However, scientific tests of many fulvic acid products have given very mixed results. A meta-analysis of 16 study cases on field application of fulvic acid was conducted. Results showed that fulvic acid could increase the average particle size of soil aggregates, but had a weak effect on the improvement of capillary porosity. Compared with control, application of fulvic acid can generally reduce soil electrical conductivity by 0.15 dS $m^{-1}$. However, for field with high groundwater level and poor discharge, the effect of fulvic acid on promoting salt leaching downward is not good. Fulvic acid treatment reduced soil pH from 8.48 to 8.38, a decrease of 0.1, yet for fields with high $[CO_3^{2-}]+[HCO_3^-]$ content, soil pH may increase after fulvic acid application. The mechanisms of fulvic acid on reducing soil electrical conductivity and pH was mainly though colloid absorption and ion exchange. Fulvic acid can promote the absorption of nutrients such as nitrogen and phosphorus by crops, and increase crop yield by 40.5%. Fulvic acid had a better effect on amelioration of moderate saline-alkali land.

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# Salinity management when irrigating with non-conventional water sources

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**ABSTRACT**

Water scarcity and climate change threaten irrigated agriculture, particularly in dry locations. Semi-arid and arid regions are typically the first to utilize non-conventional, often low-quality (high salinity) sources of water for irrigation. The need for leaching salts out of the root zone mobilizes contaminants and pollutants, including but not exclusive to the salts themselves, to deep soils and groundwater. In many cases of arid regions where there is no natural hydrological flow to the sea, strategies built on the utilization of low- or marginal-quality water are, in the long term, not environmentally sustainable.

Treated wastewater brings potentially positive additions of plant nutrients along with risks to crops, the environment, and human health, including salinity, disease agents, and numerous other contaminants of concern. Desalination offers an opportunity to reduce the leaching-contamination cycle, decrease water requirements, and increase the sustainability of irrigated arid-region agriculture. But, desalination comes at a relatively high price due to energy and facility costs. Inland desalination of brackish water and desalination of wastewater are additionally challenged with the question of brine disposal.

The Israeli experience can be used to demonstrate the costs and management challenges when irrigating with water containing relatively high concentrations of salts (brackish groundwater and recycled municipal wastewater) and how large-scale desalination of seawater can influence dry-region irrigated agriculture via both direct and indirect (via recycled wastewater) use. A decision support tool (ANSWERapp: https://app.agri.gov.il/AnswerApp/) that considers crop response to environmental conditions, including water and salt balance calculations in the root zone, is used to demonstrate agronomic and environmental repercussions of irrigation as a function of water salinity while considering processes specific to soil, weather, and crop. The app couples crop response prediction to farm and water costs and benefits, and thus allows calculation of the water required to minimize negative environmental effects and maximize profits.

# Enhancement of Organic Matter in Saline-Alkali Soils: Mechanisms and Technologies

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## ABSTRACT

Saline-alkali lands represent vital land resources and potential grain baskets, yet their productivity enhancement faces multiple constraints: high salinity levels resistant to reduction, low organic carbon content with slow accumulation rates, and nutrient deficiencies with low use efficiency. Among these, organic matter improvement serves as the foundation for productivity enhancement and nutrient retention, while also providing an effective pathway for salinity mitigation. This report synthesizes theories and technologies related to organic matter enhancement in saline-alkali soils, addressing: the mechanisms behind slow organic matter accumulation, the role of microorganisms in soil organic carbon sequestration, and differences in carbon stabilization mechanisms between lightly and moderately saline-alkali soils. It further outlines strategic pathways for carbon enhancement and stabilization, introduces technologies including multi-source organic amendment for rapid carbon increase, negative priming-induced carbon conservation, and microbial assimilation for carbon sequestration, while proposing future research priorities for organic matter improvement in degraded saline-alkali landscapes.

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# Escaping Salinity, Cyclone and other Coastal Hazards for Crop Production through Early Sowing in Wet Soils with Strip Tillage

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## ABSTRACT

Salinity, cyclone, early tidal water flooding and many other coastal calamities are increasingly threatening crop production in the Ganges delta coastal ecosystem; furthermore conventional (traditional) full tillage practices worsen the situation through delayed sowing of dry season crops until January. The aim of the study was to evaluate strip tillage technology for enabling early sowing of dry season crops in wet soil condition immediately after monsoon (*Aman)* rice harvest, allowing dry season crops to escape salinity and other coastal hazards. Field studies were conducted during the 2022-2024 dry seasons using maize and wheat as the test crops where strip tillage was compared with conventional full tillage under different doses of phosphorus fertilizer application. Conventional tillage was done after soils became dry during 5-10 January, and strip tillage was imposed immediately after harvesting of previous *Aman* rice during 10-15 December in moist soil condition. Strip tillage advanced sowing date by 20-25 days over conventional tillage. Salinity starts to build up from early February and it reached a peak in March-April; with onset of monsoon rain and it gets declined from late May. Results revealed that the grain yield of maize varied from 9.88 to11.2 t $ha^{-1}$ in strip tillage and 9.28 to 10.7 t $ha^{-1}$ in conventional full tillage endorsing consistently increased maize yield in strip tillage by 5-12% over conventional tillage. The wheat yield under strip tillage was 3.84-4.26 t $ha^{-1}$ while the conventional tillage method yielded only 1.51-2.09 t $ha^{-1}$, which was two-three times higher than the conventional tillage. Strip tillage had allowed harvesting of wheat crop by the 3$^{rd}$ week of March and maize crop by the 1$^{st}$ week of May; whereas in conventional tillage crop harvesting was done in the first week of April and the last week of May, respectively. This result indicates that reproductive stage of crop (wheat) was complete before peak time of salinity. In maize, cob initiation and reproductive stage ended before mid-March which otherwise facilitates overcoming salt stress in grain filling stage. Moreover, strip tillage also helps escape crop damage caused by extreme cyclone events in May. Early sowing through strip tillage thus not only improved crop yield and also reduced the risk of crop loss due to salinity, cyclone and other coastal calamities. Therefore, early sowing with strip tillage can sustainably intensify dry season crops in the coastal fallow lands and enhance resilience in climate-vulnerable agro-ecosystems.

**Keywords:** Salinity, cyclone, Ganges floodplain, strip tillage, tidal flooding, climate resilience

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# Sustainable Management of Saline and Sodic Black Soils in the Lowlands of Eastern Georgia

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**ABSTRACT**

Soil salinisation and sodification are the primary forms of land degradation in the dry subtropical zones of Eastern Georgia, particularly in the arid lowlands of Kakheti. This study aims to characterise the properties of saline and sodic black soils developed under agricultural use in the Sighnaghi Municipality and to determine parameters describing the degree of sodicity using the sodium adsorption ratio and the exchangeable sodium percentage.

Soil samples were examined for pH, $CaCO_3$, humus, soluble salts, texture and exchangeable cations. The studied soils were characterised by alkaline pH, moderate carbonate content and medium to high humus content. The soluble salts content did not exceed 0.75 dS/m in most cases suggesting non-saline conditions.

Exchangeable calcium dominates in the CEC, while exchangeable sodium accounts for 3–39% of it. According to the ESP, most topsoil layers are slightly sodic (3–10%), subsoils are moderately sodic (10–25%), and occasional samples show strong sodicity (>25%). Correspondingly, SAR values range from 2.6 to 37.5 meq/100 g and show a positive correlation with ESP.

A direct correlation was also observed between alkalinity (pH >8.5) and exchangeable $Na^+$, confirming the predominance of sodification. Textural analysis shows a high clay content unfavourable for crop production and promoting physical degradation.

The study concludes that the black soils of Sighnaghi lowlands are variably affected by sodification, mainly in subsoil layers, under arid climatic conditions.

Sustainable agricultural use of these soils requires integrated reclamation measures, including gypsum application, leaching with fresh water, drainage improvement and crop rotation with salt-tolerant species. These measures are essential to restore soil structure, enhance fertility and prevent further degradation.

This research provides a scientific basis for developing site-specific management practices for saline and sodic soils in the Eastern Georgian lowlands, thereby contributing to sustainable agricultural use and long-term preservation of soil fertility.

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Soil salinity, exchangeable sodium, sustainable soil management, agricultural lands

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# Quinoa as a Food Security Crop for Salt-affected and Dry Land Farming Systems

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**ABSTRACT**

Climate change is resulting in severe decline in crop yields around the world due to enhanced soil salinity, heat and drought stress. Quinoa (*Chenopodium quinoa* Willd) has been regarded as an important crop for food security under the changing climatic conditions. The combined effects of soil salinity, drought and heat stress on two genotypes of quinoa (Titicaca, Puno) were explored during a field experiment conducted on salt affected soil under dryland conditions. The joint stress of salinity, high-temperature and drought was more detrimental for plant growth and grain yield in contrast to individual stresses. The combined stresses caused 36, 41%, and 35 and 43% decline in plant biomass and grain yield Puno and Titicaca, respectively. Likewise, relative water contents and stomatal conductance in both genotypes also declined in the same way. Plants accumulated the highest K and lowest Na in the shoot when heat and drought stress were imposed along with salt stress. The mineral contents in grains such as Zn, Ca, Fe, Mg, K, Mn and Cu) also reduced more under the combined stresses of salinity, drought and heat. The contents of carbohydrates, proteins and lipids in grain were not affected by salinity alone but declined when salinity was combined with heat and drought. Plant growth, grain yield and quality was better in case of Puno compared to Titicaca. Henceforth, Puno genotype should be cultivated on salt affected soils under dry land farming systems prune to heat stress.

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# Identification of Salt-Tolerant Barley Genotypes Using Multiple Traits Index and Nutritional Performance at Early Growth Stages

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**ABSTRACT**

Soil salinity is a major constraint to sustainable agriculture, impairing soil chemical balance, nutrient availability, and crop productivity in arid and semi-arid regions. Barley (Hordeum vulgare L.), a moderately salt-tolerant cereal, offers potential for cultivation on saline soils if tolerant genotypes are identified and effectively managed. This study aimed to identify salt-tolerant barley genotypes and evaluate their phosphorus (P) accumulation and nutritional performance under salinity stress. Twenty-one barley genotypes with contrasting salinity tolerance were grown under controlled glasshouse conditions at the University of Western Australia between May and July 2024. Treatments consisted of two salinity levels (0 and 200 mM NaCl) and two phosphorus levels (low and high) arranged in a randomized complete block design with four replicates. Growth parameters, chlorophyll content (SPAD), photosystem II efficiency (Fv/Fm), and P concentrations in shoots and roots were measured after 10–12 weeks. Statistical analyses confirmed significant effects of treatments and genotypes ($P < 0.05$). Salinity stress markedly reduced shoot and root P content, with shoot P declining from 0.24% under high P and low salinity to 0.09% under low P and high salinity. Genotypes G-6, G-7, and G-17 maintained superior P accumulation and biomass under salinity stress, reflecting higher nutrient-use efficiency and physiological resilience. Enhanced P uptake under saline conditions suggests improved ion balance and reduced $Na^+$ toxicity in the root–soil interface. These findings advance genotype-based soil management strategies that enhance nutrient resilience and support sustainable agricultural productivity in saline-affected regions

**Keywords:** soil salinity, barley genotypes, phosphorus

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# Impact of neglected and underutilized species (NUS) on marginal lands: a potential tool for the recovery of soil functionality

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**ABSTRACT**

The Mediterranean region, one of the world's most important biodiversity hotspots, hosts numerous plant species naturally adapted to dry, non-fertile and saline environments. Once integral to traditional rural practices, these species, known as neglected and underutilized species (NUS), are now gaining attention for their nutritional and pharmaceutical/cosmeceutical value, as well as for their role in supporting key ecological processes. Compared with conventional crops, such as cereals and horticultural species, NUS exhibit remarkable tolerance to environmental stress and can enhance soil functionality by improving moisture retention, organic carbon accumulation, salt removal, and soil cover.

Although NUS have a negligible participation in the global agricultural market, they offer a promising opportunity to rehabilitate degraded lands, providing farmers with alternative income sources while promoting the sustainable use of natural resources.

This research aims to assess the environmental impact of introducing low-input, drought- and salt-tolerant NUS such as, *Salicornia europaea*, and *Atriplex* spp into Mediterranean farming systems affected by salinization, nutrient depletion, and desertification processes.

The study was conducted in the context of the VENUS project (https://venus-project.org/), in a reclaimed lowland area in the south of the Venice Lagoon (Italy) characterized by land subsidence, soil and groundwater salinization. Two marginal grassland pilot sites (Zennare and Gesia; total area ≈1.8 ha) managed by the Consorzio di Bonifica Adige Euganeo (CONSAE) were selected, exhibiting contrasting soil features in terms of organic matter, salinity, and acidity.

A multidisciplinary assessment was carried out, combining chemical and physical indicators (organic carbon, total nitrogen, pH, electrical conductivity) with biological metrics (soil enzymatic activity, microbial activity and biomass, nematode community structure and abundance). The results highlight the potential of NUS cultivation to foster slight yet meaningful improvements in the ecological performance, such as high biodiversity of marginal soils, supporting their progressive functional restoration, and to provide measurable agronomic benefits, reinforcing their role as a sustainable tool for climate-resilient land management in the Mediterranean region.

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# Phosphorus Dynamics in Salt-Affected Drylands Soils: Influence of Parent Material and Agricultural Management

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## ABSTRACT

Saline and alkaline soils represent a global issue that compromises agricultural productivity, particularly in arid and semi-arid regions, where limited rainfall and high evapotranspiration exacerbate salt accumulation and nutrient imbalances. Among essential nutrients, phosphorus (P) plays a crucial role in plant growth and soil fertility. However, its availability in dryland soils is often limited due to its association with apatite and other refractory mineral phases. Therefore, understanding the processes that control P dynamics under such conditions is essential for improving nutrient management and promoting sustainable agriculture, even in salt-affected soils. This study examined the distribution and fractionation of P in cultivated and uncultivated soils developed from different parent materials across two regions of the United Arab Emirates. Sequential extraction revealed that P predominantly occurs in moderately or poorly available forms, regardless of land use. Nevertheless, both the mineralogical composition of the parent material and the irrigation regime affected P fractionation and mobility. In soils derived from gypsum-rich aeolian sands, P precipitation is mainly governed by $Ca^{2+}$ ions released through gypsum dissolution, whereas irrigation with brackish water containing sodium chloride (NaCl) and $Mg^{2+}$ salts increases P solubility through the formation of Na–P compounds. In contrast, in alluvial soils, the weathering of Fe-bearing minerals such as hornblende and chamosite under irrigation conditions promotes P coprecipitation with Fe oxides and hydroxides through ligands exchange. These findings demonstrate that P availability in arid ecosystems results from a complex interaction among parent material, mineralogy, and agricultural management. A deeper understanding of P dynamics in dryland soils is therefore essential to support sustainable soil management in these challenging environments.

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# Managing saline soil to boost crop yield and halve nitrogen losses

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**ABSTRACT**

Global soil salinity, exacerbated by climate change, unsustainable irrigation, and excessive fertilizer use, is an escalating challenge for agricultural systems. While its negative effects on crop growth are recognized, the dual challenges of yield reduction and elevated reactive nitrogen ($N_r$) losses remain poorly quantified at the global scale. Existing studies are fragmented and largely confined to local mechanisms, leaving a critical gap in understanding how salinity shapes both crop productivity and nitrogen cycling across global croplands.

To address this gap, we developed the first global nitrogen budget for saline croplands by integrating the Integrated Model to Assess the Global Environment (IMAGE) with the Coupled Human and Natural Systems (CHANS) model. Using a spatially explicit pairwise comparison framework, we quantified salinity-induced changes in nitrogen inputs, yields, and $N_r$ fluxes. We further compiled and systematically evaluated ten categories of mitigation strategies for saline croplands and conducted a global cost–benefit analysis to assess their effectiveness and regional applicability, providing actionable insights for sustainable and climate-resilient management of saline croplands.

Our results show that salinity increases nitrogen inputs by 13% (over 1 million tonnes annually), reduces nitrogen harvest by 7%, and amplifies $N_r$ losses by 61%. We further demonstrate that mitigation measures can cut $N_r$ losses by 58% (1.9 million tonnes annually), enhance yields, and generate net global benefits of US$12.6 ± 6.5 billion US dollars per year. China, Pakistan, and Indonesia emerge as hotspot regions where targeted interventions could deliver the greatest gains. These findings highlight salinity management as a critical and scalable strategy for enhancing agricultural productivity and mitigating nitrogen pollution within climate-smart agriculture frameworks.

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# Sustainability of Using Salt Affected Lands in Saline Agriculture

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**ABSTRACT**

Soil salinization and its associated consequence, soil degradation, is a serious threat to sustainable use of salt-affected soils in arid and semi-arid regions. As saline soils are the most dominant type of soil in arid and semi-arid regions, farmers' lives are dependent on saline agriculture in these unsustainable soil resources.

This study was conducted with the aim of tracking soil salinity changes in saline agriculture areas to investigate sustainability of using salt affected soil for agricultural use.

The study area located in the Semnan province in central Iran and cultivated crops were pistachio, wheat, and maize. Soil moisture and temperature regimes were identified as Aridic and Thermic, respectively. Laboratory analysis of soil samples taken from study areas was done in various years 2002, 2008 and 2018 to monitor temporal salinity changes.

Study area is in arid and semiarid part of Iran where producing crops without irrigation is impossible. Agricultural use of salt affected soils increased the need for irrigation and because of the arid climate in study area it is mainly supplied by groundwater from deep wells. Using deep groundwater due to saline parent material and rock-water reaction caused salinity to increase and therefore decrease irrigation water quality. EC of irrigation water sample from 2018 was 7.08 ds/m, which increased 15% in comparison to the year 2002. To assess the sustainability of agriculture in the study area, we compared data obtained in 2018 with data from soil analyses over the past 16 years. Long term use of saline irrigation water led to further accumulation of salt in soils and accelerating degradation of salt-affected soils in study area. Comparison of the mean values of the measured ECe (in 2018) with those of 2002 indicated that it increased by at least two to more than eight times. The main mechanism involved in salt accumulation in the study area was using saline irrigation water and irrelevant irrigation methods. During these years saline agriculture has caused soil resources to degrade, and present land use is not sustainable. The consequences of increasing salinity are reduced yields and soil and water quality in the study area. Pistachio orchards' yield decreased from 2000 kg/ha to less than 500 kg/ha per year.

The results indicated that it is not possible to use salt-affected soils for agriculture without considering sustainability and the salt balance in the root zone. The hot and arid climate combined with other environmental parameters demonstrates the unsuitability of the study area for agricultural purposes. Changing land use in the study area is very difficult due to farmers' heavy dependence on their lands to meet their needs and, indeed, their very survival. Due to the high sensitivity of the economic and social conditions in the study area, special management is needed to sustain agriculture.

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# Hybrid CNN-LSTM Model for Predicting Nitrogen, Phosphorus, and Potassium (NPK) Fertilization Requirements: Integrating Satellite Spectral Indices with Field Microclimate Data

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**ABSTRACT**

Optimizing the application of Nitrogen (N), Phosphorus (P), and Potassium (K) fertilizers is a cornerstone of precision agriculture, essential for maximizing crop yield while minimizing environmental impact. Accurately predicting crop nutrient requirements remains a complex challenge due to the dynamic interplay of spatial vegetation characteristics and temporal climatic conditions. This study proposes a novel deep learning approach to predict NPK fertilization needs by integrating freely available satellite data with field-level climate measurements. We developed a hybrid Convolutional Neural Network-Long Short-Term Memory (CNN-LSTM) model designed to process multi-modal data. The architecture features parallel branches to extract spatial features from Sentinel-2 spectral indices—Modified Soil Adjusted Vegetation Index (MSAVI), Normalized Difference Red Edge Index (NDRE), Normalized Difference Vegetation Index (NDVI), and Red Edge Chlorophyll Index (RECI)—and to model temporal dependencies from daily climate variables (temperature, humidity, precipitation, wind speed, solar radiation). Tabular data on parcel size and observation date are also integrated. The model was trained and evaluated on a comprehensive dataset of 3,208 samples from a citrus orchard in Morocco, with a strict chronological split reserving the final five months for testing. The model demonstrated exceptional predictive performance on normalized test data. For Nitrogen, the Mean Squared Error (MSE) was 0.0208, Mean Absolute Error (MAE) was 0.1132, and the coefficient of determination ($R^2$) was 0.9542. For Phosphorus, MSE was 0.0281, MAE was 0.1313, and $R^2$ was 0.9480. For Potassium, MSE was 0.0225, MAE was 0.1154, and $R^2$ was 0.9474. An ablation study confirmed the critical importance of both data modalities, revealing that the removal of climate data caused a significantly larger performance degradation than the removal of satellite data. Furthermore, the model maintained stable and accurate multi-step forecasts for up to four months ahead without retraining. This work confirms that a hybrid CNN-LSTM model can effectively capture complex spatio-temporal patterns to provide accurate, near-term forecasts of NPK requirements. By leveraging free satellite data and common climate sensors, this approach offers a practical, cost-effective, and crop-agnostic decision-support tool, empowering farmers to optimize fertilization strategies, enhance productivity, and promote environmental sustainability, particularly in data-scarce regions.

# Synergistic Control of Soil Salinity via Ridge–Furrow Cultivation, Straw Mulching, and Mechanical Desalination in the Yellow River Delta

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**ABSTRACT**

Soil salinization in the Yellow River Delta, driven by shallow groundwater and intense evaporation, threatens agricultural productivity. This study investigates the synergistic effects of ridge tillage morphology (base widths: 60/90/120 cm), straw mulching (0/5 cm), and mechanical desalination (0–3 cm scraping) on salt regulation through a 2-year field experiment (2022–2023). The study results indicated that large ridges (120 cm base width) enhanced subsurface water retention by 14.2% in the furrow layer (30–50 cm) through gravitational potential energy redistribution but amplified crest salinity (peak EC = 3.21 dS/m); straw mulching (5 cm) reduced surface evaporation by 32%, maintained soil moisture at 22.87% (vs. 17.87% in controls), and lowered electrical conductivity (EC) by 67% (0.53 vs. 1.58 mS/cm); mechanical scraping (0–3 cm) removed 2.1 kg/m²salt from the topsoil, reducing surface EC from 26.77 to 8.72 mS/cm. Integrated management (large ridge configuration + straw mulching+ mechanical desalination) achieved a root-zone desalination rate of 61.3% (0-80 cm depth) over conventional practices. This provides a viable solution for saline soil management in arid regions through morphology-mulch-desalination synergy regulation.

**Keywords:** Ridge tillage morphology; Straw mulching; Mechanical desalination; Synergistic salt control; Yellow River Delta

# GeoAI-Informed Inversion: A Hierarchical Environmental Embedding Transformer (HEET) for Interpretable Soil Heavy Metal Mapping

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**ABSTRACT**

Accurate estimation of soil heavy metal concentrations is essential for human health protection, ecological risk assessment, and soil pollution control. However, the spatial heterogeneity across diverse climatic zones, soil types, and land-use conditions poses a substantial challenge. Existing methods typically treat multi-source features as flattened inputs, thereby ignoring the hierarchical dependencies inherent in Earth surface systems, which limits their ability to generalize across heterogeneous environments. To address this limitation, we propose a Hierarchical Environmental Embedding Transformer (HEET) model for large-scale inversion of soil heavy metal concentrations. The model integrates dynamic geospatial features and static environmental priors as inputs. Specifically, a hierarchical embedding module is utilized to explicitly encode the multi-level environmental priors into a structured representation. The Transformer backbone employs this hierarchical representation within its self-attention mechanism to dynamically adjust feature importance under varying environmental conditions, thereby more accurately capturing the complex response relationships among spectra, environment, and soil heavy metal variables. Experimental results demonstrate that the proposed model consistently outperforms existing methods across diverse climatic, soil, and land-use conditions, exhibiting superior performance in widely used metrics such as R2, RMSE, and MAE. Furthermore, this study provides a novel approach for integrating geoscientific hierarchy into artificial intelligence models, enhancing both generalization and physical interpretability in remote sensing applications.

**Keywords:** GeoAI, Hierarchical environmental embedding transformer (HEET), Soil heavy metal, Remote sensing inversion

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# Halophytes reclamation soil through improving soil structures, decreasing salinity and enhancing SOC storage in coastal saline land

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## ABSTRACT

Saline land holds significant potential for carbon sequestration and serves as a crucial reserve of arable land to address global climate change and food security. However, the impact of reclaiming saline land by using *Tamarix chinensis* (*T. chinensis*) and *Suaeda salsa* (S. salsa) as pioneer plants on soil structure and soil organic carbon (SOC) storage remains unclear. To clarify the effects of these two halophytes on the physicochemical properties, aggregation structure, and SOC storage of saline land, this study conducted a field experiment on plots of *T. chinensis* and *S. salsa* land that had been cultivated for five years along the coast of the Yellow Sea, with saline bare land as the control. Compared to bare land, *T. chinensis* was found to decrease the soil bulk density by 0.19, 0.27, and 0.1 g $cm^{-3}$ in the 0–10, 10–20, and 20–40 cm soil depths, respectively. Furthermore, both *T. chinensis* and *S. salsa* also increased soil porosity by 18.95 % and 28.63 % in the 0–10 cm soil depth, and by 14.54 % and 23.66 % in the 10–20 cm soil depth, respectively. Both halophytes also significantly enhanced saturated hydraulic conductivity in the 0–20 cm depth. A significant negative correlation was observed between saturated hydraulic conductivity and total soil salt content, this correlation likely facilitated salt leaching, which in turn reduced soil sodium absorption ratio (SAR). Compared to bare land, *T. chinensis* and *S. salsa* significantly reduced the soil SAR by 217.01, 122.44, and 83.35 mmol $L^{-1}$, and 114.90, 68.63, and 25.39 mmol $L^{-1}$, in the 0–10, 10–20 and 20–40 cm soil depths, respectively. They also significantly increased macroaggregates percentage (> 0.25 mm), with *T. chinensis* exerting the most pronounced effects. Most SOC storage was concentrated in the 0–10 and 10–20 cm soil depths, and *T. chinensis* induced the greatest increase-2.44 and 1.97 times higher than that of bare land in these two depths, respectively. Structural equation modeling (SEM) analysis revealed that halophytes primarily promote SOC storage in saline land by increasing the soil carbon-to-nitrogen (C/N) ratio and the proportion of macroaggregates. This study provides a theoretical basis for the improvement engineering of saline land using T. chinensis and S. salsa as pioneer plants.

**Acknowledgments**
Acknowledgment

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# Pedogenesis and classification of halomorphic soils in the Parnaíba Delta, Brazil

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**ABSTRACT**

The coastal plain of the Parnaíba Delta, located in northeastern Brazil, constitutes a complex macro-geosystem formed during the Quaternary. This landscape represents a dynamic mosaic of fluvial (Qfa), fluvio-marine (Qpm), and eolian (Qe) sediments. The region's geomorphology, characterized by low elevation, predominantly flat relief (<3% slope), and the strong influence of the tidal saline wedge, creates ideal conditions for the development of intense halomorphic processes. This study aimed to characterize the pedogenesis, major chemical properties, and classification of these salt-affected soils, based on a comprehensive analytical dataset from 40 soil profiles collected within the Parnaíba Delta Environmental Protection Area (APA Delta do Parnaíba), in the State of Piauí, Brazil. The analytical results revealed two dominant pedogenetic pathways leading to halomorphism. The first, sodification, primarily identified within fluvio-alluvial deposits (Qfa), leads to the formation of Solonetz. Profile PD03 exemplifies this pathway, presenting a diagnostic natric horizon characterized by an abrupt textural discontinuity (a loam A horizon with 213 g $kg^{-1}$ clay transitioning to a Btv1 horizon with 548 g $kg^{-1}$ clay), an Exchangeable Sodium Percentage (ESP) far exceeding the 15% threshold (15.57% in Btv1), and high Electrical Conductivity (EC) in the subsurface (15.57 dS $m^{-1}$). According to WRB (2022), PD03 is classified as a Gleyic, Salic Solonetz. The second pathway, salinization, results in the formation of Gleysols in widespread hydromorphic settings. Profile PD24, classified as a Salic, Sodic Gleysol, exhibits extreme primary salinity, with an EC of 209.1 dS $m^{-1}$ and an ESP of 49.4% in the 0–10 cm surface layer. This condition contrasts sharply with adjacent non-saline Arenosols developed on stable eolian deposits. The distribution of these halomorphic soils is controlled by landscape position—which permits the capillary rise of brackish groundwater—and by the sedimentary parent material. The flat topography is the main determining factor driving these processes. The accurate identification and classification of this complex soil mosaic—which also includes Cambisols (e.g., PD15, a Salic, Sodic, Fluvic Cambisol) and Vertisols (e.g., PD12, a Sodic Vertisol) and is marked by combined physical constraints (sodium-induced compaction) and chemical toxicity (salinity and sodicity)—are essential for environmental zoning, agricultural management, and the conservation of mangrove ecosystems within this Environmental Protection Area.

**Acknowledgments**

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# Soil salinization reduces belowground multifunctionality and crop yield at large spatial scale

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**ABSTRACT**

Saline–alkaline land represents a substantial reserve of potential arable soil, and its restoration could greatly enhance global crop production and food security. Although soil salinization is known to impair soil fertility and reduce crop yield in local experiments, large-scale patterns of belowground ecosystem multifunctionality (EMF) and crop productivity along salinity gradients remain poorly understood. Here, we collected saline soil samples and associated crop-yield data and assessed EMF using multiple approaches based on diverse indicators representing key belowground ecosystem functions.

We found that both soil salinization and land abandonment markedly decreased belowground EMF—by up to 61%—and machine-learning analyses identified the most influential predictors across different salinity levels. Crop yield in saline cropland could be reliably predicted using EMF, and predictive performance improved further when EMF was integrated with geographic variables. Moreover, substantial yield gains may be achievable by narrowing the yield gap between current yield and the saturated yield through improvements in EMF combined with targeted agricultural practices. These findings underscore the importance of comprehensive assessment of belowground EMF for ecosystem sustainability and food security, and they offer new insights and practical guidance for the amelioration and utilization of saline–alkaline land.

# Formation Mechanism of Salt Patches and Quantitative Relationship Between Water and Salt in Coastal Salinized Farmland

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## ABSTRACT

Saline-alkali soil is a typical restrictive soil type distributed extensively across the globe. Its amelioration and utilization are of great significance for safeguarding food security and maintaining soil ecological health. In China, substantial research and amelioration efforts have been carried out targeting coastal saline-alkali soils. At present, a variety of improvement measures have generally achieved the comprehensive remediation and utilization of saline-alkali lands. Nevertheless, salt patches still scatter sporadically in the form of plaques across farmland plots. However, the formation mechanism of salt patches and their quantitative water-salt relationship remain unclear.

Therefore, based on a long-term in-situ experiment conducted in the coastal saline-alkali land of the Tiaozini Reclamation Area, Yancheng Economic and Technological Development Zone, Dongtai City, Jiangsu Province, combined with the Hydrus model, this study systematically analyzed the variations in water and salt fluxes at the boundary of salinized farmland. The results showed that the variation in water flux at the upper boundary could be roughly divided into three stages: a prolonged drought stage, an intense rainfall stage, and a moderate continuous rainfall stage. During the initial phase of prolonged drought, soil moisture decreased rapidly; subsequently, it remained stable at a relatively low level due to groundwater recharge, while surface soil salinity generally exhibited an accumulating trend. Intense rainfall events could reduce salinity content, whereas the impact of moderate rainfall was relatively weak.

Salt patch formation was most pronounced during the prolonged drought stage. Intense rainfall alleviated salt patch formation to a certain extent, but moderate rainfall failed to prevent it. Film mulching only controlled the fluctuation range of soil salinity. During the formation process of salt patches, the relative variation in soil moisture and that in soil salinity showed an overall negative correlation. Moreover, the longer the duration of prolonged drought, the more significant the correlation between soil moisture and salinity became. The variation trend of soil salinity in the 0–30 cm surface layer was consistent with the variation trend of actual boundary water flux, indicating that the characteristics of salt patch variation could be inferred from the actual boundary water flux.

Overall, salt patch formation is closely related to the variation in boundary water flux. Regulating boundary water flux can effectively mitigate the persistent salt patches in coastal salinized farmland.

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# Coupling relationship between soil salinity, nutrients, and yield during reclaiming for planting rice in saline-sodic soils

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**ABSTRACT**

Saline-sodic soils are concentrated in the western part of the Songnen Plain in Northeast China, covering an area of 3.73 million hectares. Although this soil has strong alkalinity, serious physical and chemical barriers, and is difficult to treat, due to the suitable climate and relatively abundant available water resources in this region, saline-sodic soil has become the most promising reserve arable land resource for development. After long-term production practice, planting rice has been proven to be the most feasible and successful way to develop and utilize saline-sodic land. In recent years, our group has been committed to addressing the scientific problem of poor rice growth and yield caused by salt alkali barriers and low soil fertility during the development of rice cultivation in saline-sodic land. Through long-term field experiments, we aim to reveal the mechanism of alkaline barriers on rice growth and yield improvement, analyze the interaction between salinity and soil nutrients, and clarify the coupling mechanism between salinity, nutrient and yield. Our goal is to answer the question of how to scientifically reduce salt barriers and increase fertilizer efficiency during rice cultivation in saline-sodic land, and provide theoretical basis and technical support for the establishment of scientific regulation methods in the development of rice cultivation in saline-sodic land.

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# Lab evaluation of the SoilVUE10 time domain reflectometry sensor under drying and wetting conditions of saline soils

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**ABSTRACT**

The accurate quantification of soil volumetric water content (VWC) and electrical conductivity (EC) in saline vadose zones remains a critical challenge for precision agricultural water management. This study presents a comprehensive laboratory evaluation of the Campbell Scientific SoilVUE10, a profile sensor utilizing TrueWave™ Time Domain Reflectometry (TDR), compared against the Campbell Scientific CS655 (Time Domain Reflectometry) and the Beijing Truwel SM926 (Standing Wave Ratio, 50 MHz). Experiments were conducted in large-scale glass chambers (130 cm height, 50 cm × 50 cm cross-section) packed with homogeneous and stratified profiles containing expansive clay, subjected to wetting and drying cycles with salinity levels ranging from 0.01 to 19.05 dS/m. Results demonstrate that the measurement principle dictates performance stability under saline conditions. The SoilVUE10 exhibited superior resilience to bulk EC attenuation compared to frequency-domain alternatives, maintaining the lowest Root Mean Square Error (RMSE) in high-salinity treatments provided that soil-sensor contact was optimal. However, the study identified a critical vulnerability in the SoilVUE10's rigid, threaded design during drying cycles in expansive silty clays, where soil shrinkage generated air gaps that caused significant VWC underestimation. The CS655 displayed a predictable positive bias in conductive soils—correctable via soil-specific calibration—though its larger integration volume failed to resolve sharp wetting fronts in layered profiles. The SM926, operating at a fixed 50 MHz, demonstrated high sensitivity to dielectric relaxation in saline silty clays, contradicting manufacturer claims of salinity insensitivity. We conclude that while the SoilVUE10 offers the high-resolution vertical profiling necessary for stratified soils, its deployment in expansive saline soils requires modified installation protocols, such as slurry backfilling, to mitigate contact resistance errors.

**Keywords:** saline soils; SoilVUE10 TDR; Soil volumetric water content; Soil electrical conductivity; Soil sensors

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# The improvement of yield potential through amendment of saline-alkali soils in China: from plot to regional scales

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## ABSTRACT

Saline–alkali soils, serving as the reserve resources of arable land for food security, require remediation to relieve salinization indicators and improve agricultural potential yield. Although previous studies have quantified potential yield gains on saline–alkali soils at the field scale, a systematic evaluation across regions, salinization levels, amendment measures, and crop types is still lacking, and the overall potential production and the spatial heterogeneity of yield improvement across these soils remain uncharacterized.

To address this gap, we conducted a meta-analysis of 243 peer-reviewed publications from 2000 to 2024 to quantify the effects of amendment measures on saline-alkali soil properties and crop yield in China. Then, we present a framework that integrates the Global Agro–Ecological Zones (GAEZ) model with remediation-adjusted soil salinization indicators derived from the above field-scale meta–analysis. We applied this framework to simulate wheat potential yield improvement of saline–alkali soils in a typical region with saline–alkali soils — the Huang–Huai–Hai Region (HHHR), China from 2011 to 2020, considering both perspectives of remediation measures (chemical, biological, and integrated measures) and administrative units (Shandong, Hebei+Beijing, Tianjin, Henan+Anhui, and Jiangsu).

The results demonstrated that amendments significantly improved soil properties, reducing electrical conductivity (EC) by 8.44% and salt content by 17.34%, while increasing soil organic carbon (SOC), total nitrogen (TN), available nitrogen (AN), and available phosphorus (AP) by 28.15%, 39.24%, 33.29%, and 51.05%, respectively. These improvements contributed to an average crop yield increase of 41.66%, with the most substantial effects in northeast China (76.9%) and severely saline-alkali soils (80.39%). Amendment efficacy varied by type: biological measures, primarily through organic matter input and microbial activity, were most effective in enhancing SOC, TN, AN, and AP; hydraulic measures, such as leaching and drainage, best reduced salt content; and chemical amendments, through ion exchange mechanisms, most effectively lowered exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR). Crop responses also differed: cash crops exhibited greater salt stress alleviation, whereas grain crops like rice and barley achieved higher yields and nutrient uptake. Structural equation modeling (SEM) quantified that the yield increase was primarily mediated through enhanced soil nutrients and reduced salinity, which indirectly promoted crop growth.

Spatially explicit assessment of wheat yield improvement potential in saline–alkali soils demonstrated strong consistency in potential yield improvement compared to observed field data (R2=0.7, RMSE=630 kg/ha). The soil electrical conductivity, exchangeable sodium percentage, and pH of saline–alkali soils under remediation decreased by 10.31%, 22.92% and 1.2%, respectively, in the entire region. The maximum improvement of wheat potential production under remediation in saline–alkali soils of HHHR could reach 1.26 million tons (1.03-1.79 million tons), could meet the annual wheat demand for 15.85 to 27.54 million people. Among the approaches assessed for enhancing the potential yield of saline-alkali soils, integrated measures demonstrated the better effective results. From the perspective of administrative units, the potential yield of improved saline-alkali soils in Henan and Anhui increased to 1.22 times the pre-remediation. These findings provide a mechanistic basis for designing targeted and integrated strategies for saline-alkali soil amendment in China. Our new framework for spatially explicit assessment of wheat potential yield improvement in saline–alkali soils provides a scientific basis for the sustainable development and utilization of saline–alkali soils.

**Keywords:** Saline-alkali soils; Soil amendment measures; Soil properties; Crop yield; Meta-analysis; GAEZ model

# Desalination of sabkha soils as potential source of strategic metals

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**ABSTRACT**

This study investigates saline surface soils, particularly sabkha soils—defined as coastal or continental mudflats characterized by high salinity, groundwater discharge, and evaporative mineralization—as a non-conventional source for lithium, a critical strategic metal for energy storage technologies. While salinity degrades land, it also drives the mobilization and surface accumulation of highly soluble elements. We hypothesize that elements like lithium (Li), sodium (Na), and strontium (Sr) are transported from depth via capillary action and evaporation, forming detectable geochemical anomalies in surface layers.

To test this, a refined aqueous extraction protocol was developed to enhance the recovery of these mobile elements from challenging arid substrates. The method was applied to 36 samples from the Arabian Peninsula and analyzed via ICP-OES, with all data normalized to a dry-weight basis.

Our results identified significant lithium anomalies, with concentrations in some samples reaching 258% of the background mean. Strong positive correlations between Li-K (r=0.83) and Li-Mg (r=0.84) suggest their co-migration via saline groundwater. Crucially, lithium concentrations in sabkha soils were found to be up to twenty times higher than in typical aridisols, underscoring the critical role of this specific saline environment in element enrichment.

The findings confirm that the surface geochemistry of salt-affected soils can serve as an effective exploration indicator. The presented extraction technique offers a rapid tool for early-stage lithium prospecting. Consequently, the desalination of sabkha soils could be re-envisioned not just for land reclamation, but also as a promising frontier for sourcing strategic metals, adding a new dimension to the global status and management of these problematic lands.

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# Soil Nitrogen Transformation under Organic Residue Management in Salt-Affected Soils of the Vietnamese Mekong Delta

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**ABSTRACT**

Freshwater scarcity and increasing salinity in the Vietnamese Mekong Delta have caused substantial crop losses, highlighting the urgent need to diversify cropping systems toward appropriate upland crops and to develop agronomic practices that enhance crop performance under severe conditions. This study evaluated the effects of rice straw mulching and biochar application on soil nitrogen transformation, biochemical properties, and cowpea performance in salt-affected areas of the Vietnamese Mekong Delta. Field experiments were conducted from 2021 to 2023 at Long Phu and Lieu Tu districts, Soc Trang province, where salinity intrusion and freshwater shortages occur during the dry season, within a cowpea-rice–rice cropping sequence. A two-factor factorial design was applied, consisting of rice straw mulching at rates of 0, 3.5, and 7 t $ha^{-1}$ and biochar application at 0 and 5 t $ha^{-1}$, with three replicates per treatment. Soil and plant samples from the 2023 cowpea crop were collected, and post-harvest soils were used for laboratory nitrogen mineralization experiments. The results showed that straw mulching and biochar influenced plant growth, soil properties, and nitrogen mineralization processes. Ammonium ($NH_4^+$) release during incubation was higher with biochar application at the Lieu Tu site and increased with increasing rice straw mulching rates at the Long Phu site, whereas nitrate ($NO_3^-$) release was not significantly affected by biochar, indicating its role in soil $NH_4^+$ retention. Urease activity varied between sites and was affected by both straw mulching and biochar, with the combined application of 7 t $ha^{-1}$ rice straw mulch and 5 t $ha^{-1}$ biochar resulting in the highest urease activity. Soil microbial activity, assessed by soil respiration, increased with increasing rice straw mulching rates and was further enhanced by biochar application. Cowpea SPAD values increased with higher rice straw mulching rates and were also higher with biochar application. Improvements in soil chemical properties, including increased organic matter content, enhanced cation exchange capacity, increased potassium availability, and reduced sodium concentrations, contributed to a yield increase of up to 70% under straw mulching at 3.5 and 7 t $ha^{-1}$ compared with no mulching, whereas biochar application at 5 t $ha^{-1}$ did not show a clear yield effect over the three-year period. Overall, organic residue management improved soil quality and regulated nitrogen transformation pathways, providing a basis for developing sustainable nitrogen management strategies in salt-affected soils in the Vietnamese Mekong Delta.

**Keywords:** Biochar, cowpea, rice straw mulching

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# Spatial Synergies and Trade-offs between Soil Salinity and Organic Carbon in the Yellow River Delta

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**ABSTRACT**

The transition zone between terrestrial "Green Carbon" and coastal "Blue Carbon" in the Yellow River Delta is a hotspot of anthropogenic conflict. Intensive land reclamation often severs natural land-sea connectivity, replacing saline wetlands with desalinized agro-ecosystems. Does this artificial removal of salinity—a key abiotic stressor—unintentionally dismantle the biogeochemical "locks" preserving millennia-old carbon pools? The spatial divergence between crop-driven inputs and salt-mediated sequestration mechanisms remains poorly quantified, hindering precise planning.

To bridge this knowledge gap, we used Google Earth Engine and Random Forest regression to map Soil Salinity (EC) and Organic Carbon (SOC). Integrating spectral features with field surveys, we spatially quantified EC-SOC interactions. Results reveal a distinct divergence governed by hydrological connectivity: agro-ecosystems exhibit a significant trade-off, where artificial desalination lowers decomposer metabolic costs, likely triggering "rhizosphere priming" and accelerating mineralization. Conversely, natural wetlands show a synergy above specific thresholds. This challenges the "salinity is purely detrimental" paradigm, identifying salinity as a "bioenergetic preservation mechanism" that increases decomposition activation energy, effectively "pickling" organic matter.

Practically, this study provides a pedological basis for scientifically delineating "Red Lines" (cultivated) and "Blue Lines" (ecological). We propose a dual strategy: supporting precision desalination for the "Bohai Granary" initiative, while restoring the "salinity-carbon synergy" in wetlands via re-establishing hydrological connectivity. This harmonizes regional food security with carbon neutrality, ensuring the pursuit of fertility does not compromise stability.

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# THE SPATIAL VARIATION OF SOIL QUALITY ACROSS LAND-USE AND DEPTH IN SALT-AFFECTED COASTAL SOILS: EVIDENCE FROM THE FORMER GO CONG DONG, VIETNAM

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## ABSTRACT

**Purpose**

Coastal salt-affected soils are a crucial resource for agriculture and ecosystems, but they are highly sensitive to seawater intrusion and land-use changes. This study investigates and compares soil quality across different land-use types and soil depths at varying distances from the coastline in the former Go Cong Dong area (Vietnam), to identify the land-use types and soil layers most strongly affected, thereby providing a basis for proposing sustainable soil restoration and management strategies.

**Methods**

Soil quality was assessed using the Soil Quality Index (SQI) for 180 soil samples collected from two soil layers (0-30 and 30-60 cm) across three land-use types (upland soil - US, paddy soil - PS, and natural soil - NS). The effects of land-use type, soil layer, and their interaction were analyzed using two-way ANOVA, while the relationship between SQI and distance from the coastline was described using a linear model. In addition, contributive percentage analysis was applied to determine differences in the dominant roles of soil properties in controlling SQI across distances from the coastline (group I - less than 4 km and group II - greater than 4 km) and between soil layers.

**Results**

The highest SQI was observed in US (0.57 in the 0-30 cm layer and 0.55 in the 30-60 cm layer), followed by NS (0.53 in both layers), while the lowest values occurred in PS (0.51-0.52), with statistically significant differences among land-use types. The SQI of US increased markedly with increasing distance from the coastline, particularly within group I, showing a significant linear relationship in the 0-30 cm layer, indicating an improvement in soil quality toward inland areas. For PS, SQI also increased with distance, but with a weaker explanatory power and significance only in the 30-60 cm layer, reflecting greater variability among sampling points. In contrast, no clear relationship between SQI and distance was observed for NS. Contributive percentage analysis further indicated that the dominant controls on SQI varied with distance and soil depth: within group I, US dominated SQI variation in the surface layer (31.01%), whereas PS dominated in the subsoil (19.71%). In group II, SQI variation was mainly governed by factors other than land-use type.

**Conclusions**

PS are mainly affected by salinity, US maintains higher exchangeable cations and surface P, whereas NS preserves higher OC in the subsoil. Near the coast, SQI is depth-dependently dominated by US in the surface layer and by PS in the subsoil; farther inland, SQI variation is less strongly controlled by land-use type. These findings highlight the need for multi-layer soil assessments and for prioritizing integrated management strategies in coastal areas, while future studies should expand hydrological monitoring and ion speciation analyses.

**Keywords:** Coastal salt-affected soils, distance from the coastline inland, soil layers, soil quality.

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# Spatial Distribution, Underlying Mechanisms, and Management Strategies of Soil Salinity in North China Cultivated land: A Soil Profile Perspective

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**ABSTRACT**

Soil salinization under global climate warming has become a critical challenge worldwide. Intensive agricultural activities contribute to the uncertainty of soil salinity distribution. This study focused on cultivated land in North China, where 519 whole-profile soil samples (0–120 cm, collected at 20 cm intervals) were systematically collected and analyzed. Based on these data, an integrated assessment framework was developed to accurately determine the spatial distribution patterns of whole-profile soil salinity. Furthermore, the effects of climate, topography, soil properties and cultivation practices on soil salinity were explored, with the response mechanism of whole-profile soil salinity in cultivated land to the coupled effects of climate warming and intensive agricultural activities being quantitatively revealed. The results indicated the following. (1) The spatial distribution of whole-profile soil salinity followed a northwest-low to southeast-high pattern. Based on vertical differentiation characteristics, four types of salinity distribution profiles were identified: surface aggregation profile (SAP), bottom aggregation profile (BAP), uniform distribution profile (UDP) and vibration distribution profile (VDP), with UDP (36.14%) and BAP (33.04%) predominating. (2) The ratio of evaporation to precipitation, elevation, slope, soil texture, soil pH and cultivation practices significantly affected whole-profile soil salinity, while cultivation practices primarily influenced salinity distribution in the 0–40 cm soil layer. (3) The structural equation model (SEM) results indicated that climate (Direct Path Coefficient, DPC = 0.19 to 0.36) and soil properties (DPC = 0.39 to 0.65) positively affected soil salinity, whereas topography (DPC = –0.54 to – 0.69) had a negative effect. The influence of cultivation factors on soil salinity shifted from a negative effect to a positive effect at a depth of 40 cm (DPC = –0.23 to 0.14). Overall, intensive agricultural activities did not lead to surface soil salinity accumulation. Instead, irrigation counteracted the salinity accumulation effect that was intensified by climate warming, effectively reducing surface soil salinity in the cultivated land profile. This study underscores the importance of a whole-profile perspective in managing soil salinity under the combined influence of climate warming and intensive agricultural activities. This study provides a scientific basis for developing and optimizing sustainable cultivation management strategies across scales from individual fields to regions.

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# Effects of Different Amendment Measures on the Properties of Coastal Saline-Alkali Soil and Cotton Growth in the Yellow River Delta

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**ABSTRACT**

To investigate the effects of different amendment measures on the reclamation of coastal saline-alkali soil and crop growth, a field experiment was conducted in the saline-alkali land of the Yellow River Delta. The experiment comprised six treatments: a control group (CK, no fertilization), conventional nitrogen, phosphorus, and potassium (NPK) fertilization (T1), slow-release fertilizer (T2), NPK fertilization with soil compaction (T3), NPK fertilization with ridge-furrow cultivation (T4, including the furrow bottom, T4-1, and the ridge top, T4-2), and NPK fertilization with biochar (T5). The effects of these different amendment measures on soil moisture, salinity, nutrient dynamics, and cotton growth were analyzed. The results indicated that fertilization significantly increased soil nutrient content, with the T2 treatment providing the most stable nitrogen supply throughout the cotton growth period. The T5 treatment significantly increased the soil organic carbon (SOC) content; by the boll-opening stage, the SOC content in the 0–10 cm soil layer had doubled compared to that of the control group. The T3 treatment inhibited salt leaching, leading to a maximum increase in surface soil salinity of 15.2% compared to the control. The ridge-furrow treatment (T4) induced salt redistribution, decreasing surface salinity in the furrow bottom (T4-1) while causing salt accumulation on the ridge top (T4-2) due to evaporation. Furthermore, compared to the CK treatment, all amendment measures significantly increased cotton plant height, the number of established plants, single boll weight, and seed cotton yield. Specifically, treatments T1 and T2 significantly increased the number of established plants, while treatments T2, T3, and T4 significantly increased single boll weight. Correlation analysis revealed that seed cotton yield was positively correlated with planting density and boll weight, and negatively correlated with soil salinity. A close relationship was found between cotton plant traits and soil physicochemical properties. In conclusion, each amendment measure exhibits unique advantages and limitations for the reclamation of saline-alkali soil. This study provides a valuable References for developing reclamation strategies for coastal saline-alkali land.

# Aquaculture impoundment reduces salt leaching efficiency of subsurface drainage systems in neighboring farms

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## ABSTRACT

Subsurface drainage is widely used to mitigate soil salinization in coastal agricultural systems by regulating groundwater tables. However, adjacent surface water bodies may alter regional groundwater flow and thereby affect salt leaching efficiency. In this study, subsurface drainage systems were installed at a coastal farm comprising both rice (*Oryza sativa* L.) fields and adjacent bare soil patches. Field monitoring over one year showed that soil apparent electrical conductivity decreased by 49.5% following subsurface drainage installation. Groundwater dynamics were strongly influenced by a nearby freshwater aquaculture pond. When the pond was impounded, groundwater table control by subsurface drainage became ineffective, leading to reduced salt leaching efficiency. A two-dimensional HydroGeoSphere model was employed to simulate coupled groundwater flow and salinity transport under subsurface drainage conditions, incorporating the hydraulic influence of the aquaculture pond. Model simulations reproduced the observed groundwater responses and soil salinity trends, supporting field observations. Our results indicate a shift in the dominant drivers of soil salinity dynamics: groundwater table regulation dominated salt leaching before pond impoundment, whereas rainfall became the primary control after impoundment. These findings highlight the importance of accounting for nearby surface water bodies, such as land-based aquaculture ponds, when designing subsurface drainage strategies for coastal farmland salinity management.

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# Effect of salinity on soil water vapor sorption and associated hysteresis

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**ABSTRACT**

The mechanisms by which soil salinity impacts on water vapor sorption behaviors are not completely clear. The study aimed to investigate the effects of natural salts on soil water vapor sorption and associated hysteresis under different water activity ($a_w$) levels, and to elucidate the role of salt crystals in the water vapor adsorption and desorption process. We measured the water vapor sorption isotherms (WSIs) and physicochemical properties of seven soils with salt content ($Q$) ranging from 0.5 to 22.7 g kg$^{-1}$ before and after salt removal. The WSIs of low-salinity soils ($Q$ < 9.0 g kg$^{-1}$) exhibited classical Type II isotherm, but the WSIs of high-salinity soils ($Q$ > 15.7 g kg$^{-1}$) displayed atypical linear adsorption ($a_w$ = ~0.7 to ~0.85) and desorption ($a_w$ = ~0.5 to ~0.75) trends, deviating from Type II behavior. The presence of salts had little effect on water content at low $a_w$ levels ($a_w$ < ~0.4), but significantly increased water content at high $a_w$ levels (adsorption: $a_w$ > ~0.6; desorption: $a_w$ > ~0.5). The presence of salts increased local hysteresis ($H$) across all $a_w$ levels, with untreated soils exhibiting 1.3 to 6.2 times higher average $H$ values than salt-removed counterparts. The maximum $H$ differences for soils with $Q$ < 15.7 g kg$^{-1}$ occurred at $a_w$ > 0.8, while for the soil with $Q$ = 22.7 g kg$^{-1}$, it occurred at $a_w$ = 0.7. Water vapor sorption in saline and non-saline soils at low $a_w$ levels was mainly through hydration interactions. The effects of salts on soil WSIs at high $a_w$ levels were mainly attributed to the deliquescence of salts (sulfates and chlorides), increased electrostatic forces, and the osmotic potential generated by salt dissolution. The presence of salts amplified $H$ primarily through cation hydration-dehydration asymmetry at low $a_w$ levels, pore-throat blockage via capillary condensation at high $a_w$ levels, and asymmetric deliquescence-crystallization thresholds in high-salinity soils.

***Keywords:*** Soil content; Isotherm type; Adsorption; Desorption; Local hysteresis; Deliquescence; Crystallization; Osmotic potential

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# Integrating Hydrological Modeling and Explainable Machine Learning to Reveal the Key Drivers of Soil Salinization in the Huolin River Basin

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**ABSTRACT**

This study focuses on soda saline–alkali soils in the Huolin River Basin, where scarce precipitation, seasonal flow cessation, and imbalanced irrigation–drainage have led to persistent salt accumulation, while the basin-scale driving mechanisms remain poorly understood. We integrate the SWAT hydrological model with an XGBoost–SHAP framework to quantitatively identify the key controls on soil EC and ESP at the sub-watershed scale. A total of 95 sub-watersheds were delineated from a high-resolution DEM, and SWAT was calibrated to obtain sub-watershed-level runoff, baseflow, percolation, evapotranspiration, and soil water content. These hydrological variables, together with PLAND and other landscape metrics, were combined with a global EC/ESP mapping product to build regression models. The results show that hydrological and landscape factors can accurately reproduce the spatial patterns of EC and ESP (with $R^2$ for EC up to 0.94), indicating that, at the sub-watershed scale, soil salinization is no longer controlled solely by local soil and climate conditions but is dominantly driven by the joint effects of surface runoff, groundwater discharge, deep percolation, evapotranspiration, and land-use configuration. Seasonal flow interruption and irrigation–drainage imbalance markedly enhance salt accumulation in the root zone and shallow groundwater. SHAP-based composite indices of soil salinization (SSA), landscape configuration (LAN), and hydrological conditions (HYD) exhibit stable cointegration and mutual Granger causality, revealing strong bidirectional coupling and temporal lags between hydro-salinity processes and landscape evolution. These findings provide a methodological framework and quantitative basis for optimizing water diversion and drainage regimes and cropland configuration, thereby enabling basin-scale macro-control of soil salinization under different levels of water-resource security.

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# Construction of an Integrated Improvement Technology Model of "Top Promotion, Middle Modification, and Bottom Drainage" for Severe Saline-Alkaline Land in Arid Areas

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## ABSTRACT

At present, the situation regarding global farmland protection and food security remains severe. The existing farmland is mostly under high-intensity utilization, and the potential for increasing high-yield farmland is narrowing. Soil salinization is seriously threatening the productivity of global arable land, becoming a major environmental issue restricting the sustainable development of agriculture. Particularly in arid regions, severely saline-alkaline soils, due to high salt accumulation, deteriorated structure, and low nutrient availability, severely limit crop growth and sustainable land use. According to statistics, the area of land affected by salinity worldwide is approximately 950 million hectares, mainly distributed in arid and semi-arid climate zones. These regions have intense evaporation, scarce precipitation, high groundwater levels, and abundant soluble salts, making them prone to salt accumulation on the surface and the formation of secondary or primary saline-alkaline soils. In China's northwest region, a typical inland arid area, it has long been under the control of a continental climate, with evaporation several times that of precipitation. Coupled with historically unreasonable flood irrigation and the absence of drainage systems, a large amount of farmland and potential arable land has degraded into severely saline-alkaline land. Severely saline-alkaline soil is characterized by highly concentrated salts, deteriorated physical structure, imbalanced chemical properties, and reduced biological activity.

The stress caused by saline-alkaline environments on plants includes osmotic stress, ion toxicity, oxidative stress, and nutrient imbalance, significantly inhibiting seed germination, root development, photosynthesis, and dry matter accumulation, leading to reduced crop yields or even total crop failure. Traditional single improvement measures, such as simple leaching, single application of organic materials, or relying solely on drainage, are often difficult to achieve sustained and efficient salt removal and soil fertility improvement in arid regions. They have problems such as easy rebound of improvement effects, high costs, and uncontrollable ecological risks. Therefore, it is urgent to establish a systematic technical model that can simultaneously address crop stress resistance, soil modification, and salt drainage to achieve a balance between short-term benefits and long-term sustainability.

Based on the above background, this study proposed and implemented the "Top Promotion - Middle Modification - Bottom Drainage" comprehensive improvement technology model in a typical arid and severely saline-alkaline area in northwest China. It starts from the three-dimensional coordination of the crop layer, soil layer, and water-salt transport layer, aiming to break the vicious cycle of salt accumulation and soil degradation.

The overall goals of the research are:

1. To clarify the improvement mechanism of severely saline-alkaline land in arid areas under the three-layer coupling effect of "Top Promotion - Middle Modification - Bottom Drainage";
2. To verify the comprehensive effectiveness of this model in reducing soil salinity, improving physical and chemical properties, increasing crop yields, and enhancing ecological functions;
3. To provide a replicable and scalable technical model for regional agricultural ecological restoration and sustainable land use.

The theoretical framework is centered on the coupling theory of soil-plant-water systems, implementing improvement measures in a vertical layering manner: Top Promotion: In the crop layer, through agronomic and microbial measures, enhance the salt tolerance and growth potential of plants, buffering the impact of saline-alkaline stress on key life processes; Middle Modification: In the rhizosphere and plow layer, through the coordinated application of organic-inorganic-biological amendments, regulate soil physical and chemical properties, breaking the cycle of salt accumulation; Bottom Drainage: In the lower part of the soil profile, construct controllable salt transport channels, and use hydraulic conditions to guide soluble salts out of the plow layer, preventing salt from rising and flowing back. The three measures can be implemented simultaneously in time, form vertical linkage in space, and achieve a closed loop of "salt suppression - soil modification - growth promotion - salt drainage" in mechanism, thereby overcoming the limitations of single measures.

The study area is located in the southern part of Xinjiang Uygur Autonomous Region, China, in the alluvial plain between the northern part of the Tarim Basin, the southern foot of the Tianshan Mountains, and the northern edge of the Taklimakan Desert. It has a typical temperate continental arid climate, with an average annual precipitation of less than 100 millimeters and an evaporation of 2000-2500 millimeters, about 20-25 times that of precipitation. The average annual sunshine duration is 2556-2991 hours, with up to 8-9 hours in summer and about 6-7 hours in winter. The soil texture is sandy loam, with an initial salt content of 17.43 g $kg^{-1}$, pH = 8.66, organic matter of 3.71 g $kg^{-1}$, and bulk density of 1.48 g $cm^{-3}$. The experimental plots were designed in a randomized block layout, with four treatments: CK (conventional tillage as the control), T1 (upper promotion treatment), T2 (upper promotion + middle modification treatment), and T3 (upper promotion + middle modification + lower drainage (comprehensive mode)). Each treatment was replicated three times, and intervals were set between treatments to eliminate the influence of lateral water movement. The upper promotion measures included the use of mulched drip irrigation, the selection of the cotton variety "Tahe 2" and the planting of salt-tolerant crops; the application of salt-resistant and growth-promoting compound fertilizer (N-$P_2O_5$-$K_2O$ = 12-10-18) as base fertilizer; seed treatment with salt-tolerant bacteria before sowing; and drip irrigation with small amounts of water in multiple applications to keep the root zone moist without waterlogging. The middle modification measures included the incorporation of biochar (1 t/acre) and vinegar residue (1 t/acre) before plowing; the application of straw humic acid (5 kg/acre) and mineral humic acid (5 kg/acre), followed by rotary tillage to a depth of 30 cm; the inoculation of a compound microbial agent (2 kg/acre); and the spraying of a new phospholipid-based lipid preparation before sowing. The lower drainage measures involved the installation of corrugated PE plastic perforated pipes (diameter 110 mm, spacing 10 m, buried depth 120 cm), connected to a water collection well and a pump drainage system.

After one season of improvement, the physical and chemical properties of the soil changed. In the 0-20 cm soil layer of the T3 treatment, the salt content decreased from 17.43 g $kg^{-1}$ to 4.61 g $kg^{-1}$, a reduction of 73%, $EC_{1:5}$ decreased from 13.5 ms/cm to 3.15 ms/cm, and pH decreased from 8.9 to 8.3; the organic matter increased to 7.6 g $kg^{-1}$. The emergence rate of wheat in the T3 treatment increased to 80%, while that of CK was 30%. The plant height at maturity increased by 35% in the T3 treatment, and the seed cotton yield reached 378.68 kg/acre, an increase of 211.5% compared to CK. The characteristics of water and salt movement showed that the average daily drainage volume of the underground drainage system during the leaching period was 120 $m^3$ $ha^{-1}$, and the salt drainage volume was approximately 180 kg $ha^{-1}$·time, effectively preventing the capillary rise of salt. The microbial community response indicated that the Shannon index of the root zone bacteria in the T3 treatment was significantly higher than that of CK ($P < 0.05$), with the dominant phyla being Ascomycota and Basidiomycota. The abundance of salt-tolerant functional bacterial groups increased, suggesting that the amendments and microbial agents promoted the colonization and functional expression of beneficial microorganisms.

The upper promotion measures enhance the salt tolerance and stress resistance of crops through agronomic and microbial pathways. Salt-alkali stress mainly manifests as osmotic stress, $Na^+/Cl^-$ ion toxicity, and oxidative stress, which inhibit water absorption by roots, nutrient uptake, and photosynthesis. Selecting salt-tolerant varieties and combining them with salt-resistant and growth-promoting fertilizers can increase the osmotic adjustment substances and antioxidant enzyme activities in cells, alleviating ion imbalance. Inoculating salt-tolerant functional bacteria can secrete plant hormones, promote root development, and induce systemic resistance. Drip irrigation with small amounts of water in multiple applications maintains an appropriate water potential in the root zone, reducing surface salt accumulation and water waste. These measures work together to increase the salt tolerance threshold and resource utilization efficiency of crops, ensuring the accumulation of photosynthetic products and grain filling during the critical growth stages. The middle modification measures utilize the synergistic effects of organic, inorganic, and biological components to break the salt accumulation cycle. Biochar, with its porous structure and rich functional groups, can adsorb and fix $Na^+$, reduce salt activity, and improve soil porosity and infiltration performance. Vinegar residue, rich in organic acids and readily available carbon, promotes microbial activity and reduces pH, activating insoluble nutrients. Straw humic acid and mineral humic acid can fix $Na^+$ through ion exchange and complexation, improve aggregate stability and cation exchange capacity, and enhance fertilizer retention capacity. The compound microbial agent can secrete extracellular polysaccharides to promote aggregate formation, and the desalination bacteria can reduce the $Na^+$ activity in the rhizosphere. Nitrogen-fixing and phosphorus-solubilizing bacteria can enhance the availability of nitrogen and phosphorus. New lipids participate in cell membrane repair, reducing the increase in membrane permeability and ion leakage caused by salt, and stabilizing the intracellular ion homeostasis. The four types of soil amendments, namely organic, mineral, biological and lipid, work in synergy to improve the soil from physical structure, chemical properties and biological activity, breaking the positive feedback loop of salt accumulation - soil structure deterioration - biological decline. The lower layer is equipped with underground drainage pipes and leaching systems to establish a stable salt transport channel. The pipes are buried below the root zone and can collect and discharge the salt-laden water during irrigation and leaching periods, preventing capillary action from bringing salt from the lower layer back to the surface. Quantitative freshwater leaching combined with water level control can replace the high-salt water in the plow layer and lock in the salt drainage effect. This design avoids the direct discharge of high-concentration salt water into sensitive environments, achieving environmentally friendly salt management. The three-layer coupling is characterized by temporal synchronization, spatial coverage and complementary mechanisms: enhanced crop stress resistance reduces the pressure on soil improvement, the optimization of soil physical and biological properties provides a high-quality growth medium for crops, and the drainage system prevents salt backflow and locks in the results. This three-dimensional improvement based on the soil-plant-water system coupling theory significantly enhances the synergy of salt drainage, soil improvement and yield increase, verifying the scientificity and feasibility of the integrated model in the management of severely saline-alkali land in arid areas.

The "top promotion - middle improvement - bottom drainage" integrated improvement technology model has achieved significant goals of salt drainage, quality improvement, yield increase and ecological restoration under the severe saline-alkali conditions in arid areas. The core lies in promoting crop stress resistance and growth, systematically optimizing the physical and biological properties of the rhizosphere and plow layer, and ensuring the stable operation of the salt drainage channel. This model provides a replicable and scalable technical paradigm for the management of saline-alkali land in arid areas and offers empirical support for the theory of integrated management of the soil-plant-water system. In the future, our research will focus on: ① long-term effect assessment under different climate and management scenarios; ② precise optimization of amendment ratios and application methods; ③ resource utilization and environmental impact control of drainage water; ④ construction of a smart monitoring and decision support system based on remote sensing and the Internet of Things, to achieve digital and intelligent management of saline-alkali land improvement.

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# Determination of Irrigation Depth for Tomato considering the Cost for Water under a Saline Condition

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## ABSTRACT

We have presented a new scheme, “optimized irrigation”, in which irrigation depth is determined such that net income considering the price of water and weather forecasts during each interval is maximized using WASH_1D/2D which are numerical simulation models of water flow and solute transport in soils and crop growth. To evaluate whether the optimized irrigation is also able to restrict salinity stress and avoid salinization without any intentional leaching, we carried out an irrigation experiment.

A variety of Tomato was grown on a sandy loam soil in a greenhouse in Tropical Agriculture Research Front of Japan International Research Center for Agricultural Sciences using a drip irrigation system whose emitter distance was 20 cm and lateral spacing was 100 cm. On November 21, seedlings were transplanted below each emitter after exposing natural rain for six months. Two treatments were established: C: irrigated with saline water containing 2 g/L NaCl using an automated irrigation system using two soil moisture sensors, ARP WD5-WET-SDI, installed below 10 cm and leaching was carried out twice and O: irrigation depth was determined with the scheme and 2 g/L NaCl solution was used for the irrigation. Each treatment had three replicates. To evaluate if WASH_2D can predict water flow and solute movement under such condition, soil moisture and salinity sensors, ARP WD5-WET-SDI, were installed at the depths of 10 and 40 cm below emitter. The same amount of liquid fertilizer was applied to each treatment at a constant daily rate. As a result, total yield and applied water were almost the same, giving the non-significant difference in net income. If we consider depreciation expenses for the sensors, solenoid valves and controllers, net income for the proposed scheme was higher. Regarding the accuracy of simulation, fair agreement between observed and simulated water contents were obtained. These results may demonstrate the effectiveness of the proposed scheme even in saline conditions.

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# Bio-Organo Silicon Granules: A Strategy for Salinity Tolerance in Tomato

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**ABSTRACT**

Silicon (Si) amendments are well known to mitigate salinity stress in tomato (*Solanum lycopersicum*), but higher doses can result in soil fixation and associated environmental concerns. To address these challenges, we developed and evaluated a bio-organo silicon granule (BOSG) strategy that integrates silicate-solubilizing bacteria (SSB), a chemical source, and an organic carrier to alleviate salt stress. Adsorption–desorption assays in a characterized saline soil revealed a substantial Si fixation, once solution concentrations exceeded 100 ppm, with pronounced hysteresis, indicating low reversibility and minimal carryover from soluble sources. Preliminary pot screening (0-200 ppm) identified 75 ppm solution Si as an operationally efficient dose, with diminishing physiological benefits at higher levels, consistent with fixation constraints. Soil incubation over 80 days showed sustained Si delivery for approximately 60 days, followed by a gradual decline; a Weibull nonlinear model provided the best kinetic fit (median $R^2 = 0.95–0.98$; $\Delta AIC \geq 12$ vs. zero- or first-order models). In saline pot trials, BOSG 1@100 kg Si $ha^{-1}$ significantly outperformed NPK-only controls: soil-solution Si increased by 20–35%, leaf $Na^+$ content decreased by 10–18 %, and physiological indices improved (chlorophyll +8–15%, photosynthetic rate + 10–14 %, membrane stability +6–12 %), leading to biomass and marketable yield gains of 12–22 %. Overall, these findings demonstrate that saline soils strongly immobilize Si above -100 ppm, that -75 ppm solution Si maximizes efficiency in this soil–crop system, and that SSB-enabled BOSG 1 @100 kg Si $ha^{-1}$ offers a lower-input, sustained-release strategy to mitigate salinity stress in tomato, meriting field-scale evaluation.

**Keywords:** *Silicate-solubilizing bacteria; Salinity tolerance; Adsorption–desorption; Release kinetics; Bio-Organo Silicon Granules*

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# Saltwater intrusion impact on coastal agricultural soils of Los Lagos Region, Chile

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**ABSTRACT**

A comprehensive soil survey program is urgently needed to evaluate the impact of saltwater intrusion on the salinity of coastal agricultural soils in Chile, particularly in communes projected to experience intensified issues due to climate change. This study aims to investigate changes in soil salinity along a gradient of saltwater intrusion in coastal agricultural soils. The study sites are located in three distinct hydric soils with varying soil properties: the Maullín estuary, characterized by beach ridges with sandy materials classified as Inceptisols; the Calbuco coastal area, a marine terrace comprised of a mix of materials including surface volcanic deposits, beach sands, marine fossils, and fluvioglacial materials, also classified as Inceptisols; and Chiloé Island, featuring volcanic and fluvioglacial materials classified as Andisols. These three sites have been identified as highly vulnerable to saltwater intrusion due to their low-lying topography and inadequate coastal protection. The area exhibits a temperate-oceanic climate (Cfb), with average annual precipitation ranging from 2000 to 2500 mm and annual temperatures between 13.6 and 6.3 °C. Soil samples were collected to a depth of approximately 150 cm using a bucket auger at each site along three intrusion transects (1, 2, and 3 masl), with cores segmented into five depth increments: 0-15, 15-30, 30-60, 60-100, and 100-150 cm for chemical analysis (n=5). The sampling process occurred in September 2024, during the winter season. Moreover, each experimental site was equipped with an environmental monitoring station, including sensors for measuring soil temperature, electrical conductivity (EC), and soil moisture; and a piezometer (up to 1.5 m depth) was employed at each transect to monitor water level fluctuations, as well as water EC and temperature between July 2024 and September 2025. All collected soil samples underwent standardized chemical characterization, assessing parameters such as pH, ECe, sulfate, boron, carbonate, bicarbonate, chloride, $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$. Analyses revealed that soil pH increased from moderately acidic values at the surface (pH: 5.5-6.1) to moderately alkaline values at greater depths (pH: 7.1-8.1). Similarly, ECe and salt concentrations were higher in subsurface soils (ECe: 0.41-1.92 dS/m) compared to surface soils (ECe: 0.27-0.36 dS/m). The sensor data indicated that EC levels rose as the water table fell, suggesting potential seawater intrusion or increasing salt concentrations. In groundwater, the highest EC values (2.6 dS/m) were recorded during low rainfall periods, particularly at the end of summer (March 2025). In conclusion, there is significant evidence of saline intrusion phenomena leading to the alkalinization and salinization of deeper horizons in coastal soils.

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# Mechanisms of Ammonia Volatilization Mitigation in Saline-Alkali Soils Amended with Biochar-Compost: Linking Reduced pH and Enhanced Aggregate Stability to Microbial Shifts

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## ABSTRACT

Ammonia ($NH_3$) volatilization is a major nitrogen (N) loss pathway, accounting for over 30% of the applied N in salt-affected soils. $NH_3$ emissions pose a dual environmental threat by contributing to the formation of $PM_{2.5}$ and promoting eutrophication. Nevertheless, there is a lack of research on effective control of $NH_3$ volatilization in saline-alkali soils, as well as the mechanisms by which amendments synergistically inhibit $NH_3$ volatilization through the regulation of soil physicochemical properties and microbial communities. A soil column experiment was conducted with a saline-alkali soil from the Ningxia Hetao Irrigation District to assess the impact of biochar-compost on $NH_3$ volatilization, soil properties, and microbial community. Compared to conventional fertilization (CKU), the 1% biochar-compost treatment (BCOFL) resulted in a 30.82% reduction in cumulative $NH_3$ volatilization and a 35.24% decrease in $NH_3$ flux per unit biomass. High-throughput sequencing revealed significant shifts in microbial communities under compost-based amendments: BCOFL exhibited a higher relative abundance of Firmicutes compared to the 1% compost-only treatment (OFL), with Firmicutes showing positive correlations with soil mean weight diameter (MWD) and total N ($P < 0.05$). FAPROTAX annotation indicated that N-fixing functional groups in BCOFL were 57.28% and 85.52% more abundant than those in OFL and CKU, respectively. Structural equation modeling identified reduced soil pH and increased MWD as key drivers of $NH_3$ volatilization suppression. These findings suggest that biochar-compost effectively mitigates $NH_3$ emissions by lowering soil pH, enhancing aggregate stability, and promoting N-fixing microbes, thereby demonstrating potential for improving N use efficiency and reducing N loss-related environmental risks in saline-alkali soils.

**Keywords:** Biochar-compost; NH3 volatilization; Microbial community; Saline-alkali soil; Aggregate stability

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# Optimal Groundwater Depth Thresholds for Sunflower in Salt-affected Farmland: A Process-Based Modeling Approach Across Hydrological Years in the Hetao Irrigation District

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**ABSTRACT**

In arid and semi-arid regions with shallow groundwater, soil salinization, water scarcity, and deterioration water quality are major constraints to regional agricultural development. Determining optimal groundwater depth (GWD) is essential for conserving water resources, controlling resalinization, and sustaining crop yields. However, it is not feasible to evaluate the results under various scenarios solely through field experiments. This study addresses this gap by integrating field experiments (2023-2024) with the agro-hydrological & chemical and systems simulator (AHC) to optimize GWD for sunflower cultivation under varying hydrological years and groundwater salinity in the Hetao Irrigation District (HID), China. The calibrated model simulated root zone water-salt dynamics and crop responses across scenarios, with multi-objective optimization (NSGA-II) deriving Pareto-optimal solutions for yield and salinity control. The results indicated that root zone bottom flux decreases with rising GWD, with upward water flux approaching zero at about 3 m depth and upward salt flux approaching zero at 1.5-1.9 m depth, respectively. The final yield of sunflowers was negatively correlated with groundwater mineralization, though this dependence weakens at deeper GWD (>1.8 m). The optimal GWDs for sunflower growth under dry, normal, and wet hydrological years with pre-sowing spring irrigation and rainfed conditions during the growth period were approximately 1.18-1.28 m, 1.23-1.32 m, and 1.37-1.45 m, respectively. These results demonstrate GWD's pivotal role in regulating farmland water-salt distribution, with derived thresholds enabling sunflower production while reducing root-zone salt accumulation.

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# Application of biochar in saline soils enhances soil resilience and reduces greenhouse gas emissions in arid irrigation areas

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## ABSTRACT

Quantifying soil health is crucial for evaluating and guiding soil management strategies. Soil salinization has become one of the main threats to soil health. However, the effects of biochar application on the improvement of saline soils and greenhouse gas emissions remain controversial. This study focused on spring maize fields in the Hetao Irrigation District and conducted a two-year field experiment from 2021 to 2022. Biochar derived from maize stalks at a pyrolysis temperature of 400℃ was a evenly spread over the soil surface, manually incorporated, and then rotary tilled to ensure thorough mixing within the 0–30 cm soil layer. Five field treatments were set up: CK (no fertilizer), BC0 (0 t $ha^{-1}$ biochar), BC7.5 (7.5 t $ha^{-1}$ biochar), BC15 (15.0 t $ha^{-1}$ biochar), and BC22.5 (22.5 t $ha^{-1}$ biochar). The results showed that appropriate biochar (15.0 t $ha^{-1}$) addition increased soil profile nitrate nitrogen content, 0–40 cm soil organic carbon and total nitrogen, 0–120 cm soil water storage (SWS) and electrical conductivity, as well as maize plant height, leaf area index, dry matter accumulation, grains per row, 100-grain weight, yield, and water use efficiency (WUE). However, excessive biochar application (22.5 t $ha^{-1}$) reduced the effectiveness of soil water storage, led to salt accumulation, decreased soil profile nitrate nitrogen content, and increased maize water consumption. Additionally, biochar application reduced $N_2O$ emission peaks, $N_2O$ emission factors, and cumulative emissions, while promoting soil $CH_4$ absorption. Biochar reduced cumulative soil $CO_2$ emissions, but excessive application (22.5 t $ha^{-1}$) increased $CO_2$ cumulative emissions. Sole nitrogen fertilizer application significantly increased global warming potential (GWP) and greenhouse gas emission intensity (GHGI), but the combination of nitrogen fertilizer and biochar significantly reduced GWP and GHGI. These findings provide a theoretical basis for improving the health of saline soils and mitigating climate change.

# The Construction of a Soil Profile Image Segmentation Dataset（SPISD） Based on Typical Soil Series Profile Photos from 13 Provinces in China

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## ABSTRACT

A major bottleneck restricting the widespread application of artificial intelligence in soil science is the lack of high-quality soil image datasets comparable to ImageNet in the field of computer vision. Soil profiles serve as the foundation for soil classification. By analyzing the characteristics of soil profiles, we can understand soil formation processes and predict some soil properties. Currently, the Third National Soil Census is being conducted in China, involving the excavation of tens of thousands of soil profiles and photographing them with digital cameras. However, the construction of high-quality soil profile image datasets has not yet garnered sufficient attention from soil scientists. To address this, this paper proposes a method for constructing a soil profile image segmentation dataset based on soil profile photographs using an interactive segmentation annotation tool. The aim is to initiate further efforts and encourage more soil science researchers to build soil profile image datasets, thereby providing foundational data support for applying artificial intelligence to advance the field of soil science.

We collected the provincial volumes of the *China Soil Series Records*, totaling 12 books [1-12]. From these books, we identified typical soil series profile photographs from 13 provinces (municipalities directly under the central government), including Anhui, Beijing, Fujian, Guangdong, Hainan, Hebei, Henan, Hubei, Jiangsu, Jilin, Shanghai, Tianjin, and Zhejiang. Using the scanner integrated in the MFC-7450 Brother printer, we scanned the typical soil series color photographs from the aforementioned books. The scanning parameters were set as follows: horizontal and vertical resolutions both at 96 dpi, bit depth of 32, and file type as JPG. During scanning, we ensured that the photographs in the book pages were placed straight and flat against the scanner panel to guarantee image clarity. After scanning, the scanned image files were cleaned and organized. The JPG files were loaded into the Windows Paint software to crop out the soil profile photograph sections, including the soil profile color photographs (primarily featuring three types of objects: the surface area of the profile point, the profile scale, and the main soil profile body, i.e., the soil mass) and the text indicating the soil series name below them (Figure 1).



Figure 1. Typical soil series profile photo[12] (a),EISeg software labeled soil section (b), and segmented and labeled soil profile image (c)

We used the high-performance interactive segmentation automatic annotation tool, EISeg (https://github.com/PaddlePaddle/PaddleSeg/tree/release/2.2/contrib/EISeg), developed by the Baidu PaddleSeg team, to perform interactive segmentation annotation on the pure soil body parts within the soil profile images. The segmentation annotation mode was set, and a high-precision image annotation model suitable for general scenarios was selected. The network (model) structure and loaded parameters were static_hrnet18_ocr64_cocolvis.pdiparams. Based on the soil series profile scale, we segmented and annotated the soil body part within the 0–1 meter depth of the soil profile. For soil series profiles with depths less than 1 meter, we segmented and annotated the soil body part corresponding to the actual depth. The annotation results consisted of PNG files of the pure soil body parts of the soil profiles and their corresponding label files (CSV files). The first column of the label file is the soil profile serial number, such as 33-001 in Figure 1; the second and third columns are the latitude and longitude values of the profile point (in degrees); the fourth column is the name of the province where the profile point is located; the fifth column is the number of soil horizons, and the sixth to eleventh columns are the names of the soil taxonomy: order, suborder, great group, subgroup, family, and series.

We named this soil profile dataset the Soil Profile Image Segmentation Dataset (SPISD). It comprises 1,654 typical soil series photographs from 13 provinces in China, along with segmented annotation result images and label files. It encompasses 12 soil orders, 31 suborders, 89 soil great groups, 209 subgroups, 945 soil families, and 1,638 soil series.

The potential applications of SPISD mainly include: (1) utilizing artificial intelligence deep learning techniques for soil classification research; (2) qualitative and quantitative analysis of soil color, such as color space conversion and redness rate; and (3) assisting in the prediction of soil properties.

We will share the Soil Profile Image Segmentation Dataset (SPISD) on Science Data Bank (https://www.scidb.cn) or GitHub for scientific community access.

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# Advances in Amelioration Technologies for Sodic and Saline-Sodic Rice Paddy Fields with emphasis on the Songnen Plain of Northeast China

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**ABSTRACT**

Salt-affected soils are widespread in arid and semiarid regions worldwide. It is estimated that about 955 × $10^6$ ha of land is affected by salinity and sodicity globally. Approximately 60% of the world salt affected soils are classified as sodic or saline/sodic soils. These soils suffer from severe structural degradation caused by certain physical processes (slaking, swelling and clay dispersion) and specific conditions (surface crusting and hardsetting). Consequently, water and air movement, plant-available water holding capacity, root penetration and tillage operations are adversely affected. In addition, osmotic stress, ion-specific toxicity and nutrient imbalances further constrain plant growth. In such cases, these combined physical and chemical stresses negatively affect plant root activity, soil microbial communities, and ultimately crop growth and yield.

It is estimated that about 20% of future increases in crop production will still result from land extensification. In such context, the development and effective utilization of the sodic and saline/sodic lands resource is essential for agricultural expansion to meet the food demands for the global population, which is expected to reach 9.1 billion by 2050. In such case, sodic and saline-sodic lands are not just a burden, but they are the last agricultural frontier. Resultantly, it is imperative to find ways to improve such land productivity of salt-affected soils.

From a land use perspective, the main current conversion pathways for sodic and saline/sodic soils include rice paddy fields, drylands, and grasslands, depending on water resources, technologies inputs, and economic conditions. As a moderately salinity-sensitive and sodicity-tolerant crop, rice is often recommended for desalinization and de-alkalization in salt-affected soils. Rice cultivation increases percolation rates, reduces soil exchangeable sodium percentage, and lowers soil pH through root activity. In practice, rice paddy fields are considered the most successful reclamation approach when reliable irrigation and drainage system can be guaranteed.

Correspondingly, recent advances in the amelioration processes of sodic and saline/sodic paddy fields, covering engineering, chemical, physical, biological, agronomic and integrated measures are reviewed. In particular, the contrasting effects on crop productivity following the reclamation of saline-sodic land using the "Da'an Model" as a 3G-integrated farming system including good soil, good variety and good agricultural management-implemented in the Songnen plain of northeast China are discussed. Furthermore, key priorities for rice paddy field amelioration technologies under emerging conditions are also proposed based on existing technical limitations and practical needs. These include the development and application of green long-term saline-alkali soil conditioners; high-efficiency desalination and alkali reduction technologies; saline-alkaline-tolerant, high-yielding, and high-quality rice varieties; specialized fertilizers for rice; water-saving irrigation practices; the cultivation and application of salt-tolerant and growth-promoting microorganisms; and green high-yield cultivation technologies. Collectively, this will provide theoretical and practical guidance for alleviating soil constraints, enhancing baseline soil fertility, and synergistically improving rice yield and grain quality.

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# Rice Reclamation Activates Mineral Phosphorus and Alleviates Phosphorus Limitation in Saline-Alkali Soils

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## ABSTRACT

Rice cultivation is widely applied to reclaim saline-alkali soils, yet its long-term impacts on phosphorus (P) speciation, microbial functional organization, and ecosystem-level P balance remain insufficiently resolved. Here, we integrated two long-term field chronosequence datasets (0-51 years and 0-30 years of rice cultivation) to quantify how rice-based reclamation restructures soil P pools and microbial P cycling along a salinity-alkalinity relaxation gradient.

Rice cultivation significantly decreased soil salinity and pH while increasing soil organic matter, reactive Fe/Al oxides, total P, and Olsen-P. In early reclamation stages (0-10 years), inorganic P was dominated by Ca-bound fractions, representing 57-71% of total $P_i$. With prolonged cultivation (≥20 years), the proportion of moderately labile Fe-P and Al-P increased to 40-57% of $P_i$, coinciding with higher contents of poorly crystalline and organically complexed Fe oxides. These mineralogical shifts enhanced labile and moderately labile P pools, increased microbial biomass P and phospholipid fatty acid abundance, and promoted plant P uptake, while simultaneously reducing soil P mass balance relative to short-term cultivation.

Microbial functional responses tracked these soil chemical changes. The reduction of the abundance of salt tolerance genes encoding $Na^+/H^+$ antiporters (*mnhB, mrpB, mnhC, mrpC, mnhD, mrpD, mnhG, mrpG, mnhA, mrpA, mnhE, mrpE, mnhF, mrpF, yrbG*), following the decrease of soil salinity, and their network connectivity with P cycling genes weakened. In contrast, genes associated with inorganic P solubilization (*gcd*) and organic P mineralization (*phoD*) decreased in relative abundance under long-term cultivation, whereas genes encoding low-affinity phosphate transporters (*pit*) increased, indicating a functional shift from P acquisition under limitation toward P assimilation under increased availability. Phosphorus cycling gene network complexity increased at intermediate reclamation stages (about 10 years) but declined after 20-30 years, reflecting a transition from stress-induced functional diversification to a more streamlined and efficient microbial P utilization system.

Collectively, these results demonstrate that rice-based reclamation induces a coordinated cascade of soil chemical relaxation, mineral P redistribution, microbial functional reorganization, and ecosystem-level P rebalancing. This process enhances phosphorus availability and biological uptake while reducing P surplus accumulation, thereby improving P use efficiency and sustainability in reclaimed saline-alkali agroecosystems.

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# Synergistic Effect of the Compound Conditioner of Humic Acid, Zeolite and Phosphate Rock Powder on Soil Quality and Rice Yield of Coastal Saline Soil

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## ABSTRACT

To investigate the ameliorative effects of humic acid (HA), zeolite (Z), and phosphate rock (P) on coastal saline soil, a field experiment was conducted in a rice paddy at the Cixi Modern Agricultural Industrial Park, Ningbo, Zhejiang Province, during the 2022 growing season. Five treatments were established: control (CK), HA alone, Z alone, P alone, and a full combination (F) of all three amendments. Soil physicochemical properties, aggregate size distribution and rice yield were systematically analyzed. A soil quality index (SQI) was calculated, and principal component analysis (PCA) was used to identify key driving factors. The results showed that each amendments had certain ameliorative effects: Compared to CK, HA significantly increased soil organic matter, available nitrogen, and available potassium, resulting in a 33.2% yield increase; Z was most effective in reducing total salt content and electrical conductivity (EC); and P enhanced available phosphorus content. The combined treatment (F) integrated the advantages of the individual amendments. Compared to CK, the F treatment significantly reduced total salt content by 11.8% and EC by 6.5%, while significantly increasing available nitrogen by 27.6%, available phosphorus by 32.3%, available potassium by 19.2%, soil organic matter by 8.0%, and the the weight percentage of >0.25 mm macro-aggregates by 3.12 percentage points. PCA indicated that the combined treatment simultaneously optimized principal component 1 (PC1, loaded primarily with nutrient and structure properties, loading >0.73) and principal component 2 (PC2, loaded primarily with salinity characteristics, loading >0.92). Consequently, the SQI value of the F treatment reached 0.67, a 158% increase over the CK value (0.26). In summary, the combined application of humic acid, zeolite, and phosphate rock achieved the simultaneous goals of salinity reduction, fertility enhancement, and soil structure improvement, which are difficult to accomplish with single amendments. This synergistic effect is key to significantly improving coastal saline soil quality and rice productivity, providing an effective technical model for the amelioration of such soils.

**Keywords:** coastal saline soil, soil conditioner compounding, soil quality index, synergistic regulation of saline-alkali disorders, rice yield

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# Halophyte Salt Absorption Characteristics and Biological Remediation Pathways for Saline-Alkali Lands

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**ABSTRACT**

Against freshwater scarcity, halophytes have demonstrated efficiency in rehabilitating saline-alkali soils and saline water resources. Studies on the growth, salt absorption characteristics, and the synergistic effects of irrigation leaching and salt absorption of *Suaeda salsa* under various saline drip irrigation strategies in crop fields remain limited. Therefore, this study selected *Suaeda salsa*, an annual Euhalophyte, as the research subject. Based on the groundwater salinity levels in Xinjiang, seven treatments were established considering both salinity (S, g/L) and quota (W, m³/ha) of irrigation water: $S_1W_1$, $S_1W_2$, $S_2W_1$, $S_2W_2$, $S_3W_1$, $S_3W_2$, ($S_1$: 0.40g/L (0.47 dS/m), $S_2$: 20g/L (33.60 dS/m), $S_3$: 40g/L (60.00 dS/m), $W_1$: 3415 m³/ha, $W_2$: 4854 m³/ha), and Control Group (CK, S: 0g/L (0 dS/m), W: full irrigation). Two years of field observations showed that the biomass, ash, $Na^+$ and $Cl^-$ in *Suaeda salsa* achieved the maximum values under the $S_2W_2$ treatment, the growth peaks all occurred at maturity stages; High salinity treatments ($S_3W_1$, $S_3W_2$, $S_2W_1$, $S_2W_2$) elevated soil salinity to levels that inhibited the growth or reduced the yield of glycophytes, the salt uptake from soil by *Suaeda salsa* accounted for 1.88~9.28% of the total salt brought in by irriagtion water after one growing season, indicating a negligible desalination effect; The salt removal from soil by *Suaeda salsa* under groundwater irrigation treatments ($S_1W_1$, $S_1W_2$) was up to 147~156% the salt content introduced by the irrigation water, and glycophytes would not experience significant yield reduction under this soil salinity levels. Under an irrigation quota of 3500–4854 m³/ha with water salinity of 0.81 dS/m, the model demonstrates that *Suaeda salsa* is capable of removing salts derived from both the previous and current years irrigation through rotation. The exponential model was found to better simulate and predict the normalized root length density (NRLD) distribution of *Suaeda salsa*. On one hand, the research findings provide a method for preventing and controlling secondary salinization of farmland-"Crop-halophyte rotation" can achieve the elimination of winter and spring irrigation while maintaining farmland water-salt balance, thereby conserving ecological water required for sustaining this equilibrium, On the other hand, due to their wide range of applications and high productivity in saline soils, the future development and utilization of severely saline-alkali lands should focus more on exploiting the direct economic benefits of halophytes rather than solely emphasizing their soil improvement function. Additionally, the continuous salt absorption by halophytes, and root model establish a data basis for developing root water-salt absorption and soil water-salt transport models.

**Keywords:** Saline drip irrigation; Salinized soil; Water-salt balance; Salt uptake; Root length density; *Suaeda salsa*

# Wenyao: A Domain-Specific Large Language Model for AI-Driven Saline–Alkali Land Reclamation

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**ABSTRACT**

Soil salinization and alkalization remain one of the major constraints on agricultural productivity and land sustainability worldwide. Existing reclamation practices are largely guided by empirical experience and manual interpretation of soil indicators, limiting their capacity to systematically integrate key soil-plant physicochemical and process-based parameters, including soil electrical conductivity (EC), exchangeable sodium percentage (ESP), sodicity, soil structure and aggregation, crop yield and nutrient availability into coherent decision-making frameworks. Moreover, fragmented soil knowledge and limited structured datasets have constrained the effective application of artificial intelligence in saline–alkali land reclamation.

To address these limitations, we developed *Wenyao*, a domain-specific large language model for saline–alkali land reclamation and soil amelioration. An automated pipeline was established to extract and structure saline–alkali land knowledge from the literature, explicitly linking "soil constraints–reclamation measures–amelioration effects–underlying mechanisms" to support structured cognition and causal inference. The training dataset for this model integrates more than 1,0000 peer-reviewed studies from Web of Science and CNKI together with multi-source public datasets, capturing regional heterogeneity in salinization mechanisms, soil texture, groundwater conditions, and baseline reclamation status. At the same time, we built a structured literature-derived database was constructed, comprising over 60 key parameters, including pre- and post-reclamation soil physicochemical properties (e.g., EC, pH, ESP, bulk density, aggregation, and nutrient availability) and associated plant physiological and yield responses. Finally, based on the collected data, we used low-rank adaptation (LoRA), the model was fine-tuned to enhance reasoning over soil water–salt dynamics, sodicity-driven structural degradation, reclamation measures, and yield–cost trade-offs. By optimizing the inference architecture, Wenyao enables integrated outputs that jointly consider reclamation effectiveness and economic feasibility, including soil constraint diagnosis, strategy recommendation, and outcome prediction.

Evaluations across multiple professional benchmarks show that Wenyao outperforms advanced general-purpose models, including Qwen3-Max and DeepSeek, in saline–alkali land question answering and decision-support tasks. Expert assessments based on over 200 questionnaires from more than 30 practitioners further confirm its strengths in constraint recognition, strategy optimization, and yield response prediction. Wenyao V1.0 provides a soil-process informed AI framework to support intelligent and precision-oriented reclamation of saline–alkali land.

**Keywords**

Saline–alkali land reclamation; Artificial intelligence (AI); Domain-specific large language models

**Acknowledgments**

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# Future global salinization dynamics and their coupled driving mechanisms

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**ABSTRACT**

Soil salinization, a growing global challenge, is a dynamic and multifaceted process shaped by the intricate interplay of natural environmental drivers and anthropogenic activities. Accurately predicting future trajectories of soil salinization poses a significant scientific challenge, as the underlying mechanisms driving its spatiotemporal evolution are not yet fully understood. This knowledge gap primarily arises from the complex nonlinear feedback mechanisms inherent in coupled human-environment systems. To address this challenge, we developed a multi-scale analytical framework integrating machine learning algorithms with causal inference approach to disentangle the complex interactions within these coupled systems. This comprehensive methodology was applied to a multi-source dataset encompassing climatic, topographic, edaphic, land-use, and remote sensing variables across varying spatial and temporal scales. From 1980 to 2100, our analysis reveals a pronounced global upward trend in soil salinization, with particularly accelerated rates observed across Asian and European regions. Notably, Russia and China have emerged as hotspots exhibiting the most substantial increases in salinization intensity. Our findings demonstrate that precipitation patterns and agricultural land-use changes constitute the dominant drivers shaping the future trajectory of global soil salinization dynamics. Current anthropogenic efforts to mitigate climate change appear insufficient to effectively counteract the accelerating global soil salinization process, suggesting a potential decoupling between climate change mitigation strategies and soil salinity control measures.

# Research on Salt-Alkali Tolerance Mechanisms of Characteristic Plants and Saline-Alkali Land Agriculture in Hetao-Ningxia Irrigation District

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**ABSTRACT**

As a strategic reserve resource for China in alleviating cultivated land shortage and bridging the food gap, saline-alkali land demonstrates immense potential for improvement and utilization. The saline-alkali areas in Hetao-Ningxia irrigation district are rich in halophytic plant resources, where Inner Mongolia and Ningxia account for 38.02% and 23.42% of China's total halophytic plant species, respectively. Therefore, studying the salt-alkali tolerance mechanisms of characteristic plants in Hetao-Ningxia irrigation district and saline-alkali land agriculture is crucial for exploiting the potential of saline-alkali land development and utilization, ensuring food security, and safeguarding regional ecological security. This study selected characteristic halophytic (salt-tolerant) plants in Ningxia, including *Lycium barbarum* L., sorghum, alfalfa, *Echinochloa crusgalli* var. frumentacea, *Glycyrrhiza uralensis* and *Suaeda salsa*, and adopted multidisciplinary approaches involving stress physiology, plant nutrition, molecular biology, ecology and geographic information science to carry out research encompassing the salt-alkali tolerance characteristics and biological improvement effects of different plants, the excavation and spatiotemporal expression of alkali-tolerant genes, the screening of salt-alkali-tolerant plant varieties and development of water-saving and salt-controlling cultivation techniques, as well as the spatial pattern configuration of salt-tolerant plants and construction of characteristic industrial models for saline-alkali land. The study elucidated the salt tolerance mechanisms, salt tolerance thresholds and biological improvement effects of different salt-tolerant plants, clarified the relationship between soil salt-alkali stress and crop quality, established a comprehensive evaluation method and a multi-dimensional precise identification technology system for plant salt tolerance, and proposed methods and schemes for the spatial pattern configuration of salt-tolerant crops in different types of saline-alkali land. It also analyzed the physiological and molecular mechanisms underlying drought and salt-alkali tolerance of different crops such as *Lycium barbarum* L., sorghum, alfalfa and *Glycyrrhiza uralensis*, identified 16 key drought and salt-tolerant genes with important application value including AT1, IPT and LcWRKY5, and elucidated their spatiotemporal expression mechanisms. In addition, the study screened a batch of suitable salt-tolerant crop varieties, put forward water-saving and salt-controlling cultivation techniques for different crops, constructed characteristic industrial models for the comprehensive utilization of different types of saline-alkali land, and conducted extensive demonstration and promotion of these models in Northwest China. The research findings provide a theoretical basis and practical guidance for saline-alkali land improvement and the development of characteristic industries in saline-alkali areas of Hetao-Ningxia irrigation district.

**[Keywords]:** Hetao-Ningxia irrigation district; Saline-Alkali Land; Salt-Tolerant Plants; Salt-Alkali Tolerance Mechanism; Saline-Alkali Land Agriculture

# Effects and Mechanisms of Plant Growth-Promoting Bacteria in Enhancing Salt Tolerance of Soybean in Coastal Saline Soils

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**ABSTRACT**

The use of coastal saline-alkali soils for soybean cultivation is crucial for global food security, yet high salinity severely inhibits soybean growth and production. The microbiome, often regarded as the plant's "second genome," plays a crucial role in enhancing stress resistance and fitness of plants. This study investigates how plant growth-promoting bacteria (PGPB), as functional components of this extended genome, improve soybean adaptation to saline soil. Native salt-tolerant PGPB strains were isolated from halophytes in a severely saline-alkali area along the Jiangsu coast. Among 488 salt-tolerant isolates, 35 produced IAA; 16 synthesized siderophores; and 5 secreted exopolysaccharides (EPS), with some exhibiting medium-to-high productivity levels comparable to literature reports. Using a soil-based screening system, six strains were identified that significantly alleviated salt stress in soybean seedlings, improving emergence rate, plant height, leaf area, and biomass accumulation. To elucidate the underlying mechanisms, metabolomics was employed to analyze the responses of metabolome in soybean roots inoculated with two representative strains, *Stutzerimonas kunmingensis* 246 and *Microbacterium algeriense* 266-2. The analysis revealed that both strains enhanced osmoregulation and activated the valine-leucine-isoleucine biosynthesis pathway. Strain 246 uniquely elevated antioxidant metabolites (citrerosein and 5-valerolactone) and the membrane-stabilizing compound Oleanane-2H,+1O,1COOH,O-HexA-HexA, while enriching the alanine-aspartate-glutamate pathway. Strain 266-2 upregulated stress-related signaling molecules and ROS scavengers and modulated the pantothenate and CoA biosynthesis pathway, potentially supporting ion homeostasis, membrane integrity, and energy supply. Field trials confirmed that these strains promoted soybean growth, nodulation, and yield in saline soil. This study demonstrates that specifically tailored PGPB can significantly improve crop resistance under salt stress, thereby providing a viable microbial strategy for sustainable production in saline-alkali soils.

# Identification of the dominant constraint factors in sodic saline-alkali paddy soils

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**ABSTRACT**

Globally, more than 800 million hectares of land are affected by salinity and sodicity. These soils are classified into acidic, neutral, and alkaline types, each exhibiting distinct chemical properties. As one of the three largest sodic saline-alkali soil distribution regions in the world, the Songnen Plain of Northeast China contains>3.73 million ha of land estimated to be affected by sodicity, which is characterized by high alkalinity (pH 8.5-10.5), high exchangeable sodium percentage, and poor permeability. Experience shows that rice culture combined with continuous flooding-drainage management is the most cost-effective way to leach salts, increase organic matter and inhibit surface alkalization. However, >90 % of newly reclaimed paddy fields in these regions are classified as moderate-strong sodic saline-alkali, rice yields in sodic saline-alkali soils have remained relatively low, typically ranging from 0.7 to 6.7 t $ha^{-1}$ during the initial years following amelioration. Sodic saline-alkali soils have coupled stresses of high $Na^{+}$, elevated $HCO_3^{-}$-$CO_3^{2-}$, low $Ca^{2+}/Mg^{2+}$ ratio, reductive toxicity, nutrient imbalance and osmotic stress, leading to poorly targeted amendments. Therefore, systematically identifying the dominant constraint factors in sodic saline-alkali paddy soils can provide a scientific basis for precisely selecting amendments, optimizing irrigation-drainage regimes, and formulating field management protocols-an endeavor essential for boosting the productivity of low-yield fields and safeguarding grain security in Northeast China and the northern japonica rice belt.

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# Global Salt-affected Soils Crisis: FAO's Latest Report and Strategic Responses

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**ABSTRACT**

Soil salinization constitutes a critical threat to global agricultural productivity, ecological stability, and long-term food security in the 21st century. The 2024 landmark report by the United Nations Food and Agriculture Organization, "The State of the Global Saline Soils," provides the first comprehensive global assessment on this issue in five decades. This ABSTRACT synthesizes its core findings: approximately 1.381 billion hectares of land worldwide are salt-affected, equating to roughly 10.7% of the global land area. Notably, about 10% of both irrigated and rain-fed croplands are impacted, underscoring the scale and urgency of the crisis. The report identifies climate change and unsustainable human practices as primary drivers exacerbating this process. In response, it outlines a multi-tiered strategic framework for sustainable management. At the prevention and control level, the focus is on optimized water governance—enhancing irrigation efficiency, improving drainage systems, and regulating groundwater to curb salt accumulation. At the remediation and restoration level, strategies target degraded soils through amendments (e.g., gypsum, organic matter) and bioremediation to detoxify and improve soil properties. At the system adaptation and transformation level, the report advocates for developing saline agriculture by breeding and promoting salt-tolerant (halophyte) crops and adapting farming systems to saline conditions. Finally, it stresses that reversing salinization trends and safeguarding food security demand strengthened global policy collaboration, increased investment in innovation, and enhanced worldwide monitoring and knowledge-sharing via platforms like the International Network on Saline Soils (INSAS).

**Keywords:** soil salinization; climate change; water resource management; saline agriculture; sustainable land management

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# Organic and inorganic carbon losses in straw amended saline and sodic soils

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## ABSTRACT

Soil carbon (C) is a significant regulator of atmospheric $CO_2$. However, the contribution of soil inorganic C (SIC), particularly carbonate minerals, to atmospheric $CO_2$ and its interaction with soil organic C (SOC) are neglected. We conducted a microcosm incubation experiment with 13C-labeled straw addition to investigate the mechanisms governing SOC and SIC dynamics in saline (EC = 0.75 dS $m^{-1}$) versus sodic soils (ESP = 16.8%). Saline soils stimulated straw degradation by 14.7% but exhibited 10.7% lower SOC-derived $CO_2$ versus sodic soils. This corresponded to higher microbial biomass and enzyme activity, promoting preferential degradation of straw-derived C in saline soils. Conversely, sodic soils amplified SOC priming by 8-fold due to Na+- induced aggregate collapse, elevating straw- and SOC-derived $CO_2$ in microaggregates by 13.7%–53.5%. This accelerated mineralization also intensified SIC dissolution, contributing > 60% of the total priming-induced $CO_2$ emissions. Despite C losses, straw increased C accrual in salt-affected soils via contrasting pathways: microbial assimilation into SOC (more than 74% of the new-formed C) and abiotic precipitation of pedogenic carbonates (more than 22.6% of the new-formed C). Collectively, these findings identify SIC as a dominant yet under-addressed $CO_2$ source and highlight microbial-aggregate interactions as critical for C management in salt-affected croplands.

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# Biologically Driven Remediation of Saline–Alkali Soils Using Soil Bio-activation Technology in Arid Regions

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## ABSTRACT

GreenTech (Shanghai) Agricultural Technology Co., Ltd. leverages its platform advantages to integrate a comprehensive soil bioactivation technology (SBT®) system designed for the restoration of arid and saline–alkali soils. This system combines SBT core materials with field-scale soil preparation, amendment application, and agronomic management practices to support soil assessment, improvement, and crop cultivation. SBT® has been successfully applied to more than 667 ha of desert land in Shache, Xinjiang, and has been demonstrated in Abu Dhabi, UAE, where it enabled standardized cultivation of maize, cotton, and alfalfa while significantly enhancing soil quality and agricultural productivity.

Saline–alkali soils represent a major constraint to agricultural production in arid regions, yet effective biological remediation strategies remain insufficiently understood. Field experiments were conducted in Gobi and desert soils of Xinjiang to evaluate the effects of SBT applied alone and in combination with different crops (maize, cotton, and alfalfa) on soil salinity, microbial activity, soil fertility, and plant growth. Treatments included a non-amended control (CK), SBT amendment, and combined SBT–crop systems. SBT application significantly reduced soil salinity, with markedly greater effects observed when combined with crops. In Gobi soils, total salt content declined by 28.6% under SBT alone and by 45.3–59.1% under SBT–crop treatments relative to CK. In desert soils, SBT–crop systems also significantly reduced the soil salinity, reflecting stronger physicochemical constraints.

Soil bacterial abundance increased by approximately 418-fold following SBT application and by 1,800–2,961-fold under SBT–crop treatments across both soil types. These increases were accompanied by significant enhancements in urease activity (38–76%), which was positively correlated with bacterial abundance, indicating improved nitrogen transformation and utilization. In parallel, SBT application substantially improved soil fertility. Compared with CK, soil organic matter increased by 32–68%, available nitrogen by 25–54%, available phosphorus by 18–41%, and available potassium by 15–36% under SBT–crop systems. Soil pH decreased by 0.4–0.9 units, alleviating alkaline stress and promoting microbial activity and nutrient availability. These improvements generated favorable conditions for salt leaching, microbial proliferation, and rhizosphere processes. Enhanced soil biological and chemical properties under SBT only and SBT–crop treatments translated into significantly improved crop growth performance, including greater above ground biomass, root development, and overall vigor compared with CK. Rather than operating as a discrete assemblage of materials, SBT is designed as a comprehensive technology that integrates functional bio-materials with standardized application and management processes. Implemented as an integrated technology suite, this approach enhances the efficiency, stability, and reproducibility of remediation outcomes and establishes a robust foundation for the development of a comprehensive, system-level solution for saline–alkali soil restoration. Overall, the results demonstrate the effectiveness of SBT-based cropping systems as a sustainable strategy for restoring saline–alkali soils and improving agricultural productivity in arid regions.

**Keywords:**Salinization; Desalination; Soil amendment; Microorganisms; Nutrients; Desert; Gobi

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# ON THE POSSIBILITIES OF USING NIR SPECTROSCOPY TO ESTABLISH THE GENETIC TYPE OF SOILS

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**ABSTRACT**

In the framework of this paper, the potential possibilities of using near-infrared spectroscopy to determine the genetic type of soils were studied (using the example of alluvial marshy, soddy-calcareous and brown forest soils).

For the study, soil samples were used in the form of "tablets" 0.5 g formed on a special mould, which were taken from the collection of soil samples. Later they were dried in an oven at temperature of 40-45 °C to an air-dry state. NIR spectra were recorded on a MicroNIR OnSite spectrometer (VIAVI, USA) in the range of 950–1650 nm. For each sample, 10 consecutive measurements were performed on each side of the "tablet".

Before using chemometric algorithms, the NIR spectra were subjected to preliminary processing – the calculation of 2nd derivatives according to Savitzky-Golay t. Statistical processing of the obtained second-order derivatives of the NIR spectra was performed using the Unscrambler X v.10.4.1 (CAMO, USA). To build a classification model, formal independent modelling of class analogies (SIMCA) was applied.

At the first stage, two sets were formed from the existing sample set. One of them later served to train the model (gauging set: 270 spectra for each soil type), the second was used to test the calculated model (validation set: 30 spectra for each soil type). Abnormal samples (8 pcs.) were previously excluded from each set, since their inclusion in any of the sets directly affects the values of statistical characteristics calculated when testing the model. Subsequently, for the gauging sets, preliminary classification models were built using the principal component method (hereinafter, PCA) for each of the 3 studied soil types. The purpose of the PCA is to extract the useful and noise components from a given data array. In other words, PCA reveals hidden data patterns.

Further, based on the calculated confidence intervals around each class, using SIMCA, the final classification model was built for the 3 studied classes, which had a 93% prediction accuracy within the gauging set. Next, the distances between the studied classes (soil types) were calculated; the obtained values are from 214.9 to 6519.4, which is considered suitable for reliable differentiation of the studied objects.

The practical possibilities of using the obtained classification model were tested on 90 samples of the variational set, each of which was projected onto the PC space corresponding to each class, based on the Euclidean distance, it was concluded about its belonging to the class. As a result, it was found that the accuracy of the classification model on the validation set is 91.1 %. At the same time, 2 out of 30 studied samples were not classified for alluvial marshy soils, 3 for soddy-calcareous soils, and one sample for brown forest soils, respectively; one sample for soddy-calcareous and brown forest soils was assigned to another class.

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# Differentiation of Urban Lawn Soils on the Basis of a Combination of Physico-Chemical Methods(for Forensic Purposes)

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**ABSTRACT**

Urban soils of Minsk are subject to intense man-made environmental impact from emissions from stationary and mobile sources of pollution. Currently, more than 300 industrial enterprises are functioning within the city, contributing their emissions to the air basin. The majority of atmospheric emissions come from large industrial facilities and heating enterprises. The cumulative impact of pollution sources causes varying intensity of input and heterogeneity in the composition of soil-contaminating substances. Furthermore, vehicle emissions directly impact the formation of soil properties of lawns located along highways.

Lawn soils are artificially created anthropogenic soils formed by mixing mineral soil (loamy sand, sand) and peat. Their chemical and agrochemical composition is determined primarily by the composition of the mixed soils and their ratios. Meanwhile, the man-made environmental impact (including the use of winter de-icing agents, and emissions from traffic and industry) results in soil salinization, heavy metal pollution, and the accumulation of solid anthropogenic particles. This results in the formation of soils having specific properties that differ from natural soil types.

In Belarus, lawn soils located along highways are frequently used in forensic soil studies, particularly in traffic accident cases. A comprehensive study of their physico-chemical properties was carried out to determine the possibility of differentiation. Soils from 14 lawn areas, located in different districts of Minsk along major highways with the most intensive traffic, were studied. Each area consisted of six 10x10m sites, spaced 50m apart. Four soil samples were collected from each site, from a depth of 0-5 cm.

The conducted research identified characteristics that can be used to differentiate urban lawn areas. Variations in urban lawn soil properties were studied in space and time.

It was established that differentiation is possible based on indicators such as granulometric composition, color, organic matter content, total and specific percentages of solid anthropogenic inclusions, chlorine, sodium, and potassium content, and heavy metal content (cadmium, lead, zinc, copper, and nickel). It was also found that the soils from 14 urban lawn areas differ from each other in their consistent variability in IR spectrometric parameters. The SIMCA classification model, developed using IR spectra, is capable of distinguishing between areas with an accuracy of 98.88±3.46 (%) for the training set and 97.32±4.92 (%) for the test set.

The obtained results form an informational and References database of indicators of soil-technogenic origin for assessing data from comprehensive forensic soil study of urban lawn areas, as well as other technogenically contaminated areas.

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# Patterns of formation of the soil cover of historical urban parks (using the example of St. Petersburg, Russia)

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**ABSTRACT**

The soil cover of cities is characterized by patchiness, associated with spatial neighborhood and alternation in time the different types of land use on the same spot. The goal of this study is to find soil cover patterns and predict them based on natural and anthropogenic factors of soil formation in urban parks with Saint Petersburg as an example.

Saint Petersburg is located in the northwestern part of Russia; total city area is 1439 $km^2$ (city center and suburbs). There are 90 parks and 136 gardens on this area. Saint Petersburg was built on terraced low plain; the historical center mean elevation is 5 m above sea level. Due to the prevalence of waterlogging processes, flat relief, high groundwater table and/or poor water permeability of sediments, the general tendency of soil cover transformation for urban greenery was to reduce excessive moisture and to provide fertile humus layer for plants. The soil cover of 3 urban gardens, 3 urban and 2 suburban parks were mapped on a scale 1:500 and 1:2000 to find patterns of its formation.

Analysis of large-scale and detailed soil maps have shown that the main type of soil transformation was caused by the drainage systems construction and surface filling. Other types of anthropogenic impacts reflected in the soil cover, both accidental and purposeful, are differentiated depending on specific locations. In parks, created on the site of a natural landscape, the soil cover patterns reflected the park layout and history of its formation, which allows predicting the localization of anthropogenic soils on its territory. The greatest degree of the soil cover transformation and its maximum taxonomic homogeneity were observed in small historical gardens of the city center, where natural soils are totally absent and soil cover consist from Urbic Technosols only. In large urban parks, along with anthropogenic soils, natural soils and their mildly transformed varieties are represented. The greatest diversity of soil cover components was found in spacious suburban parks, where the greater variability of natural factors combinations and wider range of anthropogenic impact varieties were observed. In large suburban and urban palace and park complexes the share of different anthropogenic soils and component diversity of soil cover is greater in areas adjacent to palace and estate buildings, due to both the specifics of park layout and a higher probability of soils accidental transformation and littering with construction debris there. Thus, the soil cover in suburban parks have been formed by superimposition of anthropogenic impact on natural regularities. To study the soil cover of such objects, it is necessary to consider the spatial confinement of different forms of purposeful anthropogenic impact, as well as the fact that a significant part of accidental soil disturbances associated with the vicinity of buildings, facilities and main roads within the park.

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# Cultural layer in urban soils of Saint Petersburg, Russia

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**ABSTRACT**

*Introduction.* Cultural layer in urban soils reflected historical specifics of the city and its certain areas. At the same time, cultural layer is the basis of surface soils formation. Moreover, deep strata of cultural layer could be surfaced during excavation works. Therefore, features of cultural layer are significant both in pedological and environmental aspects.

*Objects and methods*. Saint Petersburg is the second largest city of Russia, founded in 1703. The total urban area is 1439 $km^2$. The objects of this study are Saint Petersburg anthropogenic urban soils, located in parks, gardens and city streets. Totally 203 profiles were studied. pH, EC, C org., mobile P content in Olsen extraction, heavy metals (HM) –Cu, Pb and Zn (by ICP-MS, AAS and XRF methods) were determined in soil samples. Semi-quantitative phase composition of cultural layer was done with Rietveld method (desktop diffractometer Rigaku "MiniFlex II"). Past 3.12 was used for statistical data processing. The total content of artifacts (wt.%) was determined and then the artifacts were extracted by sieving, examined and photographed in 3D using a Leica stereo binocular and then studied using a scanning electron microscope with an X-ray probe Hitachi 3000 at the SPbSU Resource Center “Center for Microscopy and Microanalysis”.

*Results*. Total thickness of surface anthropogenic (cultural) layer in studied urban soils of Saint Petersburg is 0.5-2.0 m (up to 2.5-3.0 m). Cultural layer consists from fill (fine-grained material, matrix) and artifacts. Depending on the history of the city locality, the thickness of cultural layer and the artifacts content vary considerably. According to phase analysis, mineral matrix of studied cultural layer is similar with natural parent material except for calcite presence. Several types of anthropogenic inclusions were identified: 1) bricks; 2) lime mortar; 3) glass; 4) slag; 5) bones; 6) paint particles; 7) metal fragments; 8) fragments of ceramics, including tiles; 9) coal and charcoal; 10) solid food remains, except for bones - fish scales, egg shells. Construction debris quantitatively prevails. Less stable artifacts (mortar) undergo weathering with a decrease in particle size. The chemical composition of artifacts is characterized by high heterogeneity associated, among other factors, with the processes of their transformation in the soil. Artifacts in soils may contain HM (slag), but they may also serve as geochemical microbarriers where individual HMs are precipitated (bones, mortar, etc.).

Chemical properties of cultural layer are typical for urban soils: pH – 6.0-8.9; C org. is 2.5-3.5 % (up to 5-7 %), $CaCO_3$ – 0.3-35.6%. Mobile P content is high and very high. Maximum values of heavy metals (mg/kg): Zn - 1200, Pb - 1850 mg/kg, Cu - 680 mg/kg. These values are 15-90 times higher than background, i.e. inherited from natural parent materials.

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# Carbon dioxide emissions from technogenic soils of the Central forest steppe

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**ABSTRACT**

In an era of intensive industrialization and increasing consumption of mineral resources, the problem of anthropogenic transformation of landscapes has taken on a global scale. Open pit mining is one of the most aggressive impacts on the natural environment: it leads to the formation of extensive post-technogenic landscapes with totally disrupted soil and vegetation, hydrological regime and biodiversity. In addition to the quarries, a huge area is occupied by waste rock dumps that have remained uncultivated for decades. Such areas become sources of erosion, dust, water and soil pollution, reduce the aesthetic and recreational value of the landscape. Reclamation is the main way to restore the damaged areas.

Disturbed lands contribute significantly to greenhouse emissions, with multiple emission mechanisms. Several studies have estimated that the $CO_2$ emissions from post-technogenic areas can be 2 to 5 times higher than the background values for natural landscapes of the same geographical zone. The long-term carbon footprint of mining areas is often not included in national greenhouse gas inventories.

The $CO_2$ emission on the waste rock dumps under forest recultivation was studied in the Central forest steppe zone of Russia, Voronezh region. The sand and sand-chalk mixtures occupy a leading position among overburden rocks in many mineral deposits. It is characterized by poor agrochemical and water-physical properties. The object of research is the dump area called the «Orlov log». It was created in 1972 by hydraulic washing of sand and chalk mixture. Later there were implemented a large-scale forest planting program, mainly of Scots pine (*Pínus sylvestris* L.).

The intensity of $CO_2$ emissions from soil was measured in forest recultivated sites on the growing season 2025 (from the first decade of June to October), using a closed chamber method with a portable gas measurement system LI-870SC ($CO_2/H_2O$) based on gas analyzer (LI-COR Biosciences Inc.). Measurements were carried out at a time when the $CO_2$ flows are close to the daily average emission values. During the measurements the layer of forest litter not removed. At each point, the $CO_2$ emissions were measured (in triplicates with calculation of average sizes and confidential intervals). The Stevens HydraProbe soil temperature and moisture sensor was placed in the soil directly near each point, recording the characteristics of the soil at the time of measurement. Data from field measurements of $CO_2$ emissions were processed in the specialized software SoilFluxPro v5.3.1 (LI-COR Biosciences Inc., 2024).

The average rate of $CO_2$ emission in technogenic soils covered with forests plantation was 2.68 ± 1.02 μmol $CO_2/m^2$ s, ranging from the lowest values in September - 1.56, to the highest values in July, reaching, in individual measurements - 7.68 μmol $CO_2/m^2$ s. The dynamics of carbon dioxide emissions in our studies have a gradually rising trend from the beginning of June, the maximum rate of $CO_2$ release from soil is observed at the end of July and then a gently declining trend towards the end of the growing season.

The reclamation of landscapes and soils in areas disturbed by mineral extraction is critical for reducing environmental stress and greenhouse gas emissions, for returning land to the economic and natural cycle. Without systematic scientific support, the recovery processes will remain fragmented and inefficient, and accumulated environmental damage will increase.

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# Urbanization Affects Soil Microbiome Profile Distribution in the Russian Arctic Region

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**ABSTRACT**

Urbanization in the Arctic results in considerable and still poorly known environmental consequences. The effect of urbanization on soil microbiome – an ecosystem component highly sensitive to anthropogenic disturbance – remains overlooked for the Arctic region. The research compared chemical and microbial properties of the natural Podzol soils and urban soils of Arctic cities (Murmansk and Apatity), which located on Kola Peninsula. A particular attention was given to the profile distribution, which is almost completely ignored by most microbial studies. Soil microbiome was investigated by the quantitative indicators based on fluorescence microscopy (microbial biomass), PCR real-time methods (amount of rRNA genes copies of archaea, bacteria and fungi) and molecular genetic method (taxonomic and functional diversity). The principal changes in urban soils' properties compared to the natural References included a shift in pH and an increase in C and nutrients' contents, especially remarkable for the subsoil. The numbers of rRNA genes copies of archaea, bacteria, and fungi in urban topsoils were lower than in Podzol; however, the opposite pattern was shown for the subsoil. Similarly, the total microbial biomass in urban topsoils was lower compared to the Podzols, while urban subsoil microbial biomass was 2-2.5 times higher than in the natural conditions. Both for urban and natural soils and throughout the profiles, fungi were dominated by mycelium forms; however, the ratio of mycelium: spores were lower, and the amount of thin mycelium was higher in urban soils than in natural Podzols.

Functional richness of microbial communities was higher in natural Podzols, while the highest taxonomic diversity of bacteria and fungi occurred in the urban topsoil horizons. Aerobic chemoheterotrophs were universally dominant in bacterial communities in both urban soil and Podzol, with their abundance increasing in urban soils. Ectomycorrhizal fungi predominated in fungal communities in Podzol, with pathogenic and parasitic forms having minimal abundance; the contribution of saprotrophs increased in urban soils.

Urbanization in the Arctic altered soil morphological and chemical properties and created a new niche for microbial development in urban subsoils, which contribution to biodiversity and nutrient cycling will become increasingly important under projected climate change.

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# Relationships between soil health and dynamics of soil potential pathogenic microbiota in functional domains of Xi'an urban greenspaces, China

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**ABSTRACT**

Soil potential pathogenic microbiota exacerbate the environment and human health through invading normal tissues of the human body, but their distributions and interactions across functional domains in urban greenspaces are poorly understood. Herein, we collected soil samples from parkland and residential land to explore the relationships between soil health and the dynamics of soil potential pathogenic microbiota. Soil organic matter-associated properties, soil multifunctionality and health were significantly about 30% higher in parkland, but soil stoichiometry including C/N, C/P, and C/N/P were lower in parkland. Alpha diversity of soil pathogenic bacterial communities was higher than for fungal communities in residential land. The relative abundances of the dominant genera *Mycobacterium*, *Metarhizium*, and *Cladosporium* that may cause chronic lung and gastrointestinal diseases in humans were greater for residential land. Potential connected networks including soil pathogenic bacterial and fungal phylotypes were more complicated and stable in residential land, based on higher total and positive connections and higher robustness. Meanwhile, bacterial phylotypes belonging to the genus *Shigella* were identified as keystone species in parkland network, all of which were chronic pathogens. Soil total nitrogen and phosphorus as dominant properties had greater total effects on soil health in parkland and residential land, respectively. In general, soil health was mostly affected by soil multifunctionality in parkland, but was subject to higher explanation in residential land. These findings underscore intimate relationships between soil health and the dynamics of soil potential pathogenic microbiota in urban greenspaces, which has implications for human daily outdoor routines and urban habitability.

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# Specific Features of Constructozems Functioning in Cities of the Steppe and Subtropical Zones of Southern Russia

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## ABSTRACT

Anthropogenic soils in two cities of Southern European Russia were studied: the Rostov agglomeration, a major industrial center in the steppe zone, and the Federal Territory "Sirius" (FT Sirius), a recreational and tourist hub established on the Olympic legacy in the subtropical zone of the Black Sea coast. Monitoring in the Rostov agglomeration encompassed ten sites located in park and residential areas, whereas in Sirius, fifteen sites were examined within park-recreational zones and surrounding sports facilities.

Despite differences in their age and history, both cities are dominated by urbic technosols, a significant portion of which are artificially created soils – constructozems. A key unifying feature is that in both the steppe and subtropical zones, the surface recultivation layer was formed using the humus-accumulative horizons of Haplic Chernozems. These horizons are diagnostic for the Recultivation-Humus Horizons (RAT) typical for the southern European part of Russia. The study focused not only on the morphological features of constructozems under different climates but also on the transformation of various carbon forms during the early stages of their evolution. The selected monitoring sites represent the main variants of recultivated urban soils.

Despite being geographically remote from native Chernozem areas, the thickness of the RAT horizons of constructozems in FT Sirius varies widely, ranging from 5 to 55 cm, with an average of 26.4 ± 14.5 cm. In contrast, in the Rostov agglomeration, the maximum thickness of the RAT horizons does not exceed 40 cm, with an average of 18.3 ± 9.8 cm.

Soil carbon content is mainly determined by the initial humus concentration of displaced soil masses, the development intensity of grass root systems, the granulometric composition, and the intensity of pedestrian loading.

The level of $CO_2$ emissions from Rostov-on-Don urbic technosols, which constitute the components of humus horizons, is in close ranges, often below background values. This is due to the high stability of the humus complex of old arable soils, whose humus-accumulative horizons served as the parent material for the technosols. The majority of humus substances in the RAT horizons are associated with clay minerals and non-hydrolyzed residue, which results in their low mineralization propensity even when displaced and subjected to additional wetting.

In contrast, the recultivation-humus horizons of the urbic technosols in Sirius also formed from chernozem material atypical for the region, exhibit different behavior. Here, the soil organic matter, transferred into new thermodynamic conditions, has lost its stability and is now actively mineralizing, leading to increased $CO_2$ emissions. This process, coupled with the decrease in RAT horizon densities, indicates a lack of system stability and may be an indirect confirmation of concerning adverse trends in the context of carbon neutrality for landscape decisions on the Black Sea coast.

**Keywords:** urban soils, chernozems, urbic technosols, soil organic matter.

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# Urban environmentally sensitive areas (U-ESA) in the city of Bratislava

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**ABSTRACT**

Environmentally sensitive areas within urban land (U-ESA) play an essential role in maintaining urban ecological balance and ecological safety. U-ESAs are ecological elements in and around a city that have a reduced ability to regenerate if they are somehow damaged by urbanization. Microclimatic regulation of heat capacity in built-up urban environments is strongly determined by the soil sealing i.e. by pavement, asphalt, concrete and the like. Obviously, compared to open green areas, this area contributes to extreme summer temperatures, and to the creation of urban heat islands (UHI). In terms of soil and vegetation conditions, these phenomena significantly reduce the ecological functions and ecosystem services of urban soil. For mapping of urban environmentally sensitive areas (U-ESA), soil sealed surfaces in the urbanized environment were identified, soil properties and quality, including green urban infrastructure were classified and mapped. The U-ESA assessment methodology is based on a multi-criteria approach, in which several attributes were profiled: 1. mapping of land cover/land use and soil sealing using the extended nomenclature of the Urban Atlas 2012 for the city of Bratislava, 2. modelling the occurrence of urban heat islands (UHI) and their spatial distribution using the MUKLIMO model; 3. mapping of urban soils using the concept of pedo-urban complexes (PUC) and assessing their quality; 4. identification and classification of urban vegetation types; 5. overlapping and synthesis of results using GIS tools (© ESRI ArcGIS). The main outputs: 1. geospatial information is the basis for a balanced spatial design and organization of plans and studies of cities in which environmentally sensitive areas are identified, 2. in densely built-up areas, deteriorating living conditions intensify, especially in the presence of urban heat islands (UHI) 3. soil sealing surfaces are one of the main causes of increased heat, but not entirely, polluted air and microclimatic conditions play a role. The most ecologically sensitive areas appear to be city centres which are characterized by dense historical buildings and impermeable or semi-permeable soil cover (more than 80%), where an increased effect of UHI and a reduced degree of availability of public green spaces can be observed.

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# Soil Diversity in the City of Moscow as a Mirror of Evolutionary Trends in Urban Pedogenesis.

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**ABSTRACT**

Long-lasting research on soils of the city of Moscow permitted to identify main genetic groups of urban soils. These are *quasi-native* soils preserved in urban forests and parks, *urbo-native* soils with anthropogenic horizons below 40-50 cm thick; soils of the synlithogenic trend of pedogenesis – *urbostratozems* – growing upward due to additions of urban material along with the cultural layer; *weakly developed soils* on human-made sediments; sealed soils – *ekranozems*; purposefully constructed soils – *konstructozems (*reclaimed soil-like bodies). Soil properties in this assemblage reflect both pedogenetic trends depending on the geographical location and features of urban geochemistry. The matrix for building urban soils are Quaternary deposits transported from different geomorphological areas. Geochemical features of Moscow soils are related to calcareous construction and demolition materials, industrial and transport emissions and significant aerial dust load; they all contain diverse pollutants, either organic, or mineral.

The early stages of urban pedogenesis are represented by young soils on eroded, transported and/or human-made substrates with initial shallow humus horizons, as well as constructed soils, including those with artificial lawn. In full-profile soils, *urbic diagnostic horizon* is obligatory, and its thickness serves as a divide between urbo-soils and urbostratozems, its properties are described and substantiated by its origin. It is composed of periodically deposited layers – strata – of human-made materials, urban dust and waste, thus corresponding to the synlithogenic trend of soil formation, namely, soil formation synchronous to the deposition of parent material.

Soils in Moscow with a thick urbic horizon (> 40-50 cm) are qualified for *urbostratozems* – archetypal soils for settlements on the one hand, and final result of urban soil evolution on the other hand. The unity of the mineral matrix in the landscape-geomorphological areas, the geochemical background and bioclimatic conditions on the city territory allows us to speak about the genetic relationship between soils of the city and the unified pattern of urban soils evolution.

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# Threshold sand content of sand-clay mixtures is affected by clay mineralogy and compaction effort

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**ABSTRACT**

Imported soil mixtures are used in urban and trafficked areas for engineering, environmental, and agricultural applications. Sand-clay mixtures are particularly useful where dimensional stability, bearing capacity, and reduced permeability are desirable. In a coarse-grained soil, loads are borne by a skeleton of particle contacts between sand grains and soil behavior is relatively unaffected by changes in water content. Small quantities of fines have little impact on soil behavior because they fit comfortably within the intergranular voids. With further additions, the sand grains lose contact with one another and soil behavior becomes dominated by the fines and the extant water content. The sand content associated with this particle fabric has been termed the threshold sand content or TSC. TSC is often defined in the literature as the sand content yielding maximum bulk density (i.e. minimum porosity or void ratio). The TSC value will vary for any unique pair of sand and clay components because the particle arrangement is governed both by the sand-size distribution and the plasticity of the clay phase. Knowing TSC for a given clay soil can inform mix design for structural applications (where maximum density is desirable) and agricultural/environmental applications (where sand content must exceed TSC to preserve larger voids for plant growth and water infiltration).

The objective of this research was to discern how clay mineralogy, mixture ratio, and compaction effort influence the threshold fines content of sand-clay mixtures. A washed sand was mixed with either kaolinite, illite, or smectite clay at ratios ranging from 50-80% sand by dry mass. Mixtures were subjected to Proctor compaction testing using either the Standard or Modified effort. For each clay soil, the threshold sand content was defined as the sand content resulting in the lowest total porosity. TSC values ranged from 60-75% depending on clay type and compaction effort, while total porosity at TSC ranged from 21-30%. TSC was highest for smectite, intermediate for kaolinite, and lowest for illite. Additionally, TSC was higher for soils compacted using the Modified effort. This suggests that for the most accurate prediction of field behavior, TSC should not be quantified using a density-based definition, because the TSC value varies with loading conditions. It is suggested that TSC be instead defined by using mechanical soil test methods (shear strength, hydraulic conductivity, etc.) and loading parameters relevant to the application of interest.

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# Hydrothermal Carbonization of Urban Organic Waste: Is it a sustainable pathway for soil restoration in highly urbanized regions?

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**ABSTRACT**

Highly urbanized areas such as Mexico City generate large amounts of organic waste that, if not properly managed, contribute to greenhouse gas emissions and environmental degradation. **Hydrothermal carbonization (HTC)** is an emerging technology that converts humid organic residues into a carbon-rich material known as **hydrochar (HC)**, offering a sustainable strategy for both urban waste management and the recarbonization of soils. This study investigates the potential of HC produced from the organic fraction of municipal solid waste at the **Hydrothermal Carbonization Plant of Mexico City** as an organic amendment for degraded and urban soils. Controlled **incubation experiments** were conducted on six contrasting substrates (Silica sand, mining tailings, sodic soils, Acrisol, Phaeozem, Regosol) amended with **HC, pyrochar, and compost** to quantify $CO_2$ emissions and estimate carbon mineralization. In parallel, analyses of **enzyme activity** and **microbial biomass** were performed to evaluate the effects of HC on soil microbial functioning. Preliminary results indicate that HC shows relatively **low recalcitrance** but can **enhance microbial activity** depending on soil type. Degraded soils, such as saline soils and mining tailings showed an increase in organic carbon and microbial activity. Future work will focus on **conditioning treatments** to remove phytotoxic compounds and further improve hydrochar's agronomic potential. These findings highlight the promise of HTC-derived materials to integrate **urban organic waste valorization and soil rehabilitation**, advancing circular-economy strategies and climate-mitigation goals in rapidly urbanizing regions.

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# Healthy Soils for Healthy Communities – A Community-based Urban Soil Initiative from Los Angeles

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**ABSTRACT**

Soil is the brown infrastructure in cities. To better understand and utilize the potential of soils in cities, we launched the "Healthy Soils for Healthy Communities" Initiative in Los Angeles (LA), CA, United States. As the first phase of the initiative, this project aimed to determine the current status of LA County soils, identify the most pressing urban soil issues and community needs through community consultation and outreach, and provide a framework for future work regarding urban soil research, policy, public education, and community engagement in the region. We conducted four county-wide online surveys with residents, educators, policymakers, and soil-related professionals, seven focus groups with key stakeholder groups, various meetings and events, a review of the literature, and worked with universities, government agencies, non-profit organizations, and community groups to achieve these objectives. We found LA County had almost 50% impervious surfaces and 44% bare soils with 45% human altered soils. We also found resident knowledge about factors that affect soil health was low and the majority of residents (76%) are very or extremely concerned about soil contaminants and pollution in their communities. However, only 12% of them have ever tested their soils. But interest in soil-related issues is high, with 76% of participants being either extremely or very interested in the topics listed on the survey. Additionally, cross-cutting themes identified in focus groups include a need for: 1) Accessible and transparent soil data and testing; 2) Effective community engagement and streamlined communication; and 3) Building alliances among community, policy, and science professionals and leveraging organizations/ individuals/agencies already doing the work. To address the identified needs, we proposed to establish a Los Angeles Urban Soil Collaborative consisting a set of core activities, demonstration projects, community outreach programs, and the scaling up of these activities through collaborations.

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# Do local non-statutory habitat designations reflect differences in below-ground biodiversity and functioning in urban green space?

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**ABSTRACT**

Urban green spaces provide essential ecosystem services, and a range of statutory and non-statutory designations are used to protect them. However, these designations are often based on above-ground characteristics, and it remains unclear whether they also reflect belowground processes that underpin multiple ecosystem services. Here, we evaluated soil-based ecosystem processes and services in urban green spaces designated as Sites of Biological Importance (SBIs) and in adjacent, near-identical non-designated sites. We tested the hypothesis that aboveground characteristics used to designate SBIs would be mirrored by differences in soil processes supporting key ecosystem services. Seasonal dynamics of soil nutrient concentrations, soil $CO_2$ efflux (respiration), and litter decomposition were measured using a reciprocal litter transplant design to separate litter and environment driven effects. SBI designation interacted with seasonal variation, showing significantly higher soil nutrient concentrations, microbial biomass carbon, dissolved organic carbon, and improved soil water retention. Activities of oxidative enzymes (peroxidase and phenol oxidase) were also higher in SBIs, indicating an enhanced microbial capacity to process complex carbon compounds. In contrast, soil respiration did not differ between SBIs and controls and was mainly driven by soil moisture and canopy cover. The litter transplant experiment revealed a positive home-field advantage in non-designated areas but the opposite response in SBIs. Overall, these findings demonstrate that SBI designation captures important belowground differences, particularly in nitrogen-related nutrient storage and enzyme-mediated decomposition, emphasizing the broader ecological value of non-statutory designations for sustaining urban soil functions.

**Acknowledgments**

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# Assessment of trace elements mobility in Technosols developed on heaps of historical polymetallic ore mining in the Sudety Mts., SW Poland

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**ABSTRACT**

Technosols developed on historic mining waste heaps, due to the low efficiency of mining in the past, may contain large amounts of trace elements that were extracted during the mining process. As a result of soil-forming processes, these elements may be mobilized in the environment. The aim of the study was to assess the degree of mobility of selected trace elements (As, Cr, Ni, Co, Cu, Zn, Pb, Cd, Sb, Fe and Mn), in Technosols developed on the spoil heaps of historical polymetallic mining centers (mainly copper and arsenic) in Miedzianka, Radzimowice, and Czarnów in the Sudety Mts., SW Poland. Twelve soil profiles were investigated. The Zeien and Brümmer (1989) sequential extraction procedure was applied to determine the operationally defined chemical forms of selected elements – fractions (F) with decreasing mobility: F1 – mobile fraction (water-soluble and exchangeable); F2 – specifically adsorbed; F3 – bound to Mn oxides; F4 – bound to organic matter; F5 – bound to amorphous or poorly crystalline Fe oxyhydroxides; F6 – bound to crystalline Fe oxides; F7 – residue. The extracts were analyzed using ICP-OES, and mobility was assessed as a percentage of the sum of F1 and F2. The total content of the studied elements, calculated as the sum of all seven fractions, was as follows (in $mg \cdot kg^{-1}$): As (108–57407), Cu (23.2–9167), Zn (104–3191), Pb (36.9–1975), Co (22.7–760), Cr (25.4–274), Cd (3.8–217), Ni (36.9–171), Sb (0.9–61.6), Fe (50140–159019), and Mn (401–5824). Arsenic was detected mainly in F5 and F6, as well as in F7 and F4. Copper, zinc, and nickel were present in all forms, mainly in F5, F6, and F7, but a significant proportion of forms in F1 and F2 was also observed. Lead was found primarily on F4, F5, and F6. Cobalt was mainly found in F3 and F7, and in some profiles also in F1 and F2. Chromium was mainly present in F7, and to a lower degree also in F5 and F6. Cadmium occurred in various forms, mainly in F5 and F7, and also in significant amounts in F1 and F2. Antimony and iron were primarily found in F7, as well as in F5 and F6. In some profiles, a significant proportion of F4 was found. Manganese occurred mainly in F3, but also in F7, F1, and F2. The most mobile elements were cadmium and zinc (up to over 40%). The proportion of mobile manganese reached over 30%. Cobalt, copper, nickel, and antimony were also mobile (up to about 20%). The mobility of lead reached over 10%. Arsenic, iron, and chromium occurred in hardly mobile forms. The significant proportion of mobile forms of certain trace elements may pose a potential threat to the local environment due to the bioaccumulation of elements by plants or their leaching into groundwater.

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# Who Bears the Burden? Trace Element Contamination and Environmental Justice in Chicago's Urban Parks

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**ABSTRACT**

This research examines patterns and intensity of trace element contamination in soils from five urban parks in Chicago, with a focus on how soil conditions and metal concentrations relate to the socio-economic and demographic profiles of nearby communities. Portable X-ray fluorescence (pXRF) was employed to quantify concentrations of lead (Pb), arsenic (As), chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), and manganese (Mn) in collected soil samples. Results show that parks situated farther from the urban core and located in neighborhoods characterized by lower household incomes and higher proportions of minority residents, most notably Douglass and Humboldt Parks, contain markedly elevated trace element levels. Conversely, parks closer to downtown, including Grant, Webster, and Cottontail Parks, display comparatively lower contamination and are surrounded by areas with higher median incomes and property values. These patterns underscore clear socio-economic inequities in urban environmental quality. Overall, the findings emphasize environmental justice concerns, demonstrating that marginalized communities experience disproportionate exposure to contaminated urban soils. The study supports urban planning actions such as prioritizing site-specific soil remediation, encouraging safer urban food production practices, and advancing policy interventions aimed at reducing environmental health inequalities.

# Challenges for SUITMA posed by the 2025–2034 Decade of Soil Sciences for Sustainable Development

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**ABSTRACT**

Soils are increasingly threatened by degradation, sealing, contamination, and unsustainable land use, particularly in rapidly expanding urban and peri-urban areas. Recognizing the urgency of generating actionable scientific knowledge to support the UN Sustainable Development Goals (SDGs), the International Union of Soil Sciences has launched the 2025–2034 Decade of Soil Sciences for Sustainable Development (DSSSD). This global initiative aims to strengthen research, foster international collaboration, and enhance the visibility of soil functions across sectors, ensuring that soil health becomes an integral component of sustainable development policies. Within this framework, SUITMA faces specific challenges, as well as strategic opportunities, in advancing the goals of the Decade.

When properly studied, managed, and integrated into spatial planning through Nature-Based Solutions (NBS), SUITMA soils can make substantial contributions to climate-change mitigation, biodiversity enhancement, and human well-being in urban and peri-urban contexts. The effective implementation of NBS requires detailed, spatially explicit knowledge of soil properties, constraints, and ecosystem services. Such knowledge supports the definition of permeability thresholds for private and public surfaces (e.g. gardens, parking areas, sidewalks), the design and placement of water storage and drainage systems, the planning of blue–green infrastructure networks, the assessment of soil suitability for urban agriculture, the adaptation of soil management practices for parks and urban trees, the definition of rootable soil volumes needed for tree nutrition and mechanical stability, and the safe management of soils surrounding pipelines and other underground infrastructures.

Emerging technical innovations—including proximal and remote sensing, digital soil mapping, and decision-support systems originally developed for precision agriculture—offer promising tools for improving the assessment, monitoring, and management of SUITMA soils.

Strengthening soil literacy enables more transparent, inclusive, and evidence-based governance of SUITMA soils, supporting the integration of soil considerations into urban policies, land-use regulations, and planning standards. This is particularly important in UNESCO-designated areas, such as biosphere reserves and geoparks, where conservation objectives must be reconciled with development pressures.

By advancing scientific understanding and promoting targeted, context-specific management strategies, the SUITMA community can play a decisive role in achieving the objectives of the DSSSD, ensuring that urban soils contribute fully to resilient, sustainable, and inclusive cities.

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# Bioremediation of Explosive-Contaminated Soil at Military Sites: New Perspectives on Bioavailability and Ecotoxicological Effects

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## ABSTRACT

Military production, warfare, exercises, ammunition disposal, and other activities have led to widespread soil contamination with explosive compounds. Bioremediation is the optimal method for remediating explosive-contaminated soil. The research team has systematically conducted studies on the bioremediation of explosive contamination, including phytoremediation, microbial remediation, and ecological restoration. However, simply using the disappearance of TNT as an indicator still presents issues such as "incomplete degradation/residual bound forms" and "increased toxicity of intermediate products." Strengthening research on the bioavailability and ecotoxicological effects of explosives in soil will provide a basis for sustainable risk management and remediation of explosive-contaminated sites through plant/microbial-based approaches. In terms of the mechanisms of microbial deep degradation of explosive contaminants and the development of artificial transformation systems, multi-omics approaches were used to assess the micro-ecotoxicological effects of TNT and its intermediate products. A total of 22 highly efficient TNT-degrading microorganisms were screened, and a multi-enzyme cascade reaction system for deep TNT transformation was designed and constructed. The mechanisms by which synthetic microbial communities reshape the microbial ecology of contaminated soil were also investigated[1-3]. To address the issue of changes in the bioavailability of TNT and its degradation products due to interactions with soil minerals, a dark-field imaging research method was established to visualize interactions between particulate matter and organic pollutants by leveraging the light-scattering properties of particles combined with chromogenic reactions. The study found that the surface interactions between TNT and minerals/metals can be categorized into three types: physical adsorption ($Fe_2O_3$, $Al_2O$, $Fe_3O_4$, $SiO_2$, CuO, Pb), adsorption-reduction (Cu, Al), and adsorption-hydrolysis (MgO). Dark-field microscopic observation and scattering spectroscopy not only provide high spatial resolution but also reveal significant differences in adsorption between soil particles. This method plays a valuable role in studying interactions between organic pollutants and soil matrices, as well as the mechanisms governing pollutant bioavailability[4]. To address the issue of combined contamination by heavy metals and explosives at military sites, simulated soil experiments were conducted, integrating 16S rRNA gene sequencing and non-targeted metabolomics to investigate the effects of heavy metal ions (e.g., $Cu^{2+}$, $Zn^{2+}$) and nanoparticles (e.g., Cu NPs, CuO NPs, ZnO NPs) on TNT bioremediation. High concentrations of $Cu^{2+}$, $Zn^{2+}$, and Cu NPs completely inhibited TNT degradation, while ZnO NPs and CuO NPs showed partial inhibition at tested levels. Co-exposure to TNT and heavy metals significantly reduced microbial diversity. Copper and zinc heavy metals inhibited TNT-degrading microorganisms through multiple pathways, including oxidative stress, enzyme inactivation, membrane damage, and disruption of gene regulation.

**Keywords:** Explosive contamination, Bioavailability, Microbial toxicity, Multi-omics analysis, Metallic nanoparticles

**Acknowledgments**

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# Urbanization Alters Soil Nutrients and Heavy Metals in Tropical Coastal Parks: A Case Study from Haikou, China

**ABSTRACT**

Urban soil quality is critically shaped by anthropogenic activities. This study assessed the impact of urbanization intensity on key soil properties in Haikou, a tropical coastal city. Soil samples from seven parks along an urban-rural gradient were analyzed for total and available carbon (C), nitrogen (N), phosphorus (P), Fe, Al, and heavy metals (Cr, Pb, Cd, As).

Results revealed that intensive urbanization significantly altered soil biogeochemistry. Total C and N declined by up to 23%, while total P accumulated, indicating a decoupling of elemental cycles. Available nutrients shifted antagonistically, with N decreasing and P increasing, which may exacerbate N limitation and P runoff risk. The soil organic carbon pool became more labile, as evidenced by a higher proportion of particulate organic carbon, suggesting reduced long-term C stability. Concurrently, a decline in Fe and Al oxides was observed, which is critical for nutrient and contaminant sequestration. Heavy metals, particularly traffic-associated Cr and Pb, were markedly enriched in central urban parks. Multivariate analysis confirmed that anthropogenic drivers (loaded with P, Pb, Cr) increasingly overrode natural pedogenic factors (C, N, mineral-associated organic carbon, Fe) along the urbanization gradient.

We conclude that urbanization induces a synergistic pressure on urban park soils: it not only directly adds contaminants (e.g., heavy metals) but also simultaneously degrades the soil's inherent ability to mitigate these pressures (e.g., through loss of stabilizing minerals and organic matter). This combination amplifies ecological risks. Therefore, location-specific management is imperative: central urban parks require strategies focused on organic matter enhancement and heavy metal immobilization to restore buffering capacity, while peri-urban greenspaces need optimized nutrient management to prevent eutrophication. This study provides a mechanistic framework for understanding and managing soil multifunctionality in tropical coastal cities under rapid urbanization.

**Keyword:**Urban soil; Urbanization gradient; Carbon fraction; Heavy metals; Soil quality

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# The Impact of urbanization on the physicochemical properties and microbial nutrient limitations of inland wetland soils

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**ABSTRACT**

In the context of the Anthropocene, rapid urbanization has become a primary driver of land surface transformation, posing severe challenges to soil health and ecological functions of inland wetlands; however, how urbanization drives the evolution of soil properties and shifts in microbial metabolic limitations remains unclear. Here, we quantified urbanization intensity using impervious surface coverage and established 22 sampling sites across the Taihu Lake Basin, systematically analyzing soil physicochemical properties and extracellular enzyme activities to elucidate the impacts of urbanization pressure on inland wetland soil properties and microbial nutrient demands. We found that with increasing urbanization intensity, soil bulk density, pH, and concentrations of calcium, magnesium, and sodium significantly increased ($p < 0.05$), while organic carbon and ammonium nitrogen contents significantly decreased ($p < 0.05$). Enzyme activity vector analysis revealed that soil microbial carbon limitation intensified significantly with urbanization, and nutrient limitation shifted characteristically from nitrogen to phosphorus limitation ($p < 0.05$). Our findings reveal the cascading effects of urbanization-driven inland wetland soil degradation from structural deterioration to microbial metabolic reorganization, providing theoretical foundations and early warning indicators for maintaining wetland soil ecosystem functions and sustainable management in the Anthropocene.

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# Urban soils mulching: temperature and moisture regulation in urban soils under different substrates

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**ABSTRACT**

Urbanized territories in humid regions face soil degradation and disrupted water and temperature regimes. Mulching is a nature-based solution for urban soils, yet comparative substrate studies under humid conditions remain insufficient. This research examines how organic and mineral mulches regulate temperature and moisture in urban soils, informing landscape design.

The study was conducted at the instrumental sites of the soil station of Lomonosov Moscow State University during 2021-2023. The experimental design included 12 plots covered with 11 different mulching substrates of 5 cm thickness: 7 organic substrates (coconut chips, painted and unpainted pine chips, larch bark of coarse and fine fractions, pine bark of coarse and fine fractions) and 4 mineral substrates (serpentine, marble, volcanic tuff, foam glass), plus a control (bare fallow).

Soil temperature was recorded at 0 cm (directly under mulch), 5 cm, and 10 cm depth (3-hour intervals). Moisture content of the upper layer (0-10 cm) was measured during the summer periods. Characterization of mulching substrates included determination of minimum water-holding capacity (WHC).

Organic substrates showed superior WHC (54.5-83.3%) versus mineral materials (0.7-3.8%). Coconut chips had maximum WHC (83.3%). Soil moisture under mulch increases by 6.6-14.6% compared to bare fallow, with the greatest increment observed beneath fine-fraction organic substrates: coconut chips (31.0%), fine larch bark (31.8%), and fine pine bark (29.5%).

During June 2023, mineral substrates exhibited high temperature amplitudes (15.9-19.6°C at surface) due to low WHC and high thermal conductivity. Volcanic tuff showed highest amplitude (17.3°C at 5 cm) due to low albedo and enhanced evaporation. Organic substrates demonstrated stable regimes with amplitudes of 9.4-12.8°C (30-45% lower than mineral materials). Coconut chips (10.3°C) and fine larch bark (9.4°C) provided optimal buffering. Foam glass exhibited organic-like properties (11.3°C amplitude), confirming pore structure importance. At 10 cm depth, organic substrates maintained the most stable regime.

Fine-fraction organic substrates substantially increase moisture and temperature stability. Foam glass offers a promising recycled alternative. Light-colored organic materials (larch/pine bark) deliver optimal performance: maximum moisture retention and minimal temperature extremes. The correlation between water-holding capacity and temperature stability demonstrates mulching's potential as a nature-based solution for mitigating urban heat islands and supporting vegetation resilience in cities.

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# Environmental behavior of rare earth elements (REEs) in mining area: Occurrence, release, and transport

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**ABSTRACT**

Rare earth elements (REEs) are strategic resources whose intensive mining and use have led to widespread soil contamination, particularly in China. Soil colloids, the most reactive soil components, play a critical role in the occurrence, release, and transport of REEs, yet the mechanisms governing REE colloidal forms and fluxes across different mining settings remain poorly constrained. Here, we systematically investigated the occurrence, release behavior, and co-transport mechanisms of ionic and colloidal REEs across three representative Chinese REE mining types—igneous carbonate rock, igneous metamorphic rock, and ion-adsorption deposits—using ores, tailings, abandoned soils, and contaminated farmlands.

Size-resolved extractions and AF4-based analyses revealed two dominant REE colloidal fractions (5–70 nm and 250–500 nm) with distinct compositions and formation pathways. Small colloids were closely linked to mineral weathering intensity and metal (Fe–Mn) oxides, whereas larger colloids were primarily associated with clay minerals. REE fractionation differed markedly among deposit types: LREEs dominated colloids in carbonate-hosted systems, MREEs prevailed in metamorphic deposits, and mixed patterns occurred in ion-adsorption deposits. Simulated rainfall experiments showed that REE release from carbonate and metamorphic tailings was dominated by colloid-facilitated transport, while ion-adsorption systems released REEs mainly in ionic form via ion exchange and reductive dissolution, resulting in substantially higher release fluxes. Residual ammonium-based leaching agents further amplified REE mobilization from ion-adsorption tailings.

Overall, this study provides mechanistic insights into how mineralogy, weathering, and soil colloids jointly control REE occurrence, fractionation, and transport, highlighting colloid-mediated processes as critical drivers of REE pollution spread. These findings offer a scientific basis for improving risk assessment and management of REE-contaminated soils.

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# Characterization, hazards assessment and remediation of heavy metals-explosives contaminated soil in military training ranges

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**ABSTRACT**

Long-term live-training with munitions on military training ranges can lead to cumulative environmental impacts. The type and extent of contamination depends on the type of range, period of activity, soil chemistry and contaminant chemistry. Small arms firing ranges typically have high concentrations of metals and metalloids. Military ranges typically have high concentrations of energetic compounds, Such as perchlorates, white phosphorus, explosives and propellants etc. The characterization of military training ranges for energetics and metals is very important for understanding these contaminants' environmental fate and behavior, as defense agencies work to preserve ranges and prevent the migration of characteristic compounds into surface and ground waters. This paper will discuss the main techniques used for the analysis of heavy mteals and explosives in soils and water, remediation technologies for heavy metals-explosives contaminated soil. Analytic techniques focus on the areas of sample preparation and detection. For explosives, higher concentrations are found in sites that have undergone a low order detonation than in sites with a high order detonation. For heavy metals, higher concentrations are found in small arms firing ranges.

Remediation technologies for small arms firing ranges include leaching and immobilisation whereas for military ranges, methods such as alkaline hydrolysis, photolysis, bioremediation and phytoremediation have been tested. A lot of work has been done to immobilise metals/metalloids using soil amendments, which show a high effectiveness in stabilising them. Explosives can be transformed into simpler non-toxic forms by photolysis, bioremediation or phytodegradation. Explosives contaminated soils have been treated by incineration (32.1%), composting (46.5%), the redox process (1.2%), alkaline hydrolysis (12.6%) and solidification/stabilization(7.9%). Based on the results of recent pilot-scale treatability studies, in situ bioremediation has been proved to be effective in explosives contaminated soil remediation. The introduction of bacteria transgenes into plants has been used to enhance uptake and degradation of explosives in transgenic plants. Adoption of appropriate remediation technologies in impacted military ranges will reduce heavy metals bioavailability and explosives levels, inprove military soldiers health and ensure ecological environment safety.

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# Phytoremediation Potential of Native Garden Plants in Urban Soil

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**ABSTRACT**

Urban soil has been contaminated with heavy metal(loid)s (HMs) due to the legacies of long-term anthropogenic activities. These contaminants in urban soil can pose serious health risks to humans, requiring remediation strategies to restore soil quality. This study evaluated the phytoremediation potential of native plant species in HMs-contaminated soil and identified the species with superior efficiency through a pot experiment. We selected 10 species of Korean native plants (*Melica scabrosa* Trin., *Carex matsumurae* Franch., *Dystaenia takesimana* (Nakai) Kitag., *Spiraea ouensanensis* H. Lév., *Vitex rotundifolia* L.f., *Gentiana scabra* Bunge, *Allium taquetii* H. Lév. & Vaniot, *Allium spirale* Wild., *Eupatorium lindleyanum* DC., and *Eupatorium fortunei* Turcz.) and 3 exotic species (*Allium tuberosum* Rottler ex Spreng, *Eupatorium lindleyanum* 'Pink Frost', and *Spiraea japonica* 'Nana') for comparison. These seedlings were transplanted to contaminated soil (330, 13, and 415 mg/kg for As, Cd, and Pb, respectively) and non-contaminated soil. Plant growth and physiological responses were monitored for 16 weeks. Total and available concentrations of HMs in soil were quantified, and various factors related to metal uptake by plants were calculated. Each species had five replicates in contaminated soil and three replicates in non-contaminated soil. As a result, native plants such as *M. scabrosa*, *V. rotundifolia*, *E. fortunei*, and *E. lindleyanum* showed significantly higher shoot height in HMs-contaminated soil than in non-contaminated soil at Week 16. Native *C. matsumurae* and *E. fortunei* showed 103% and 13% higher dry weight (DW) in HMs-contaminated soil compared to non-contaminated soil, respectively, whereas *D. takesimana* and *A. spirale* had 54% and 27% lower DW, respectively. For photosynthetic pigments, in Week 4, *M. scabrosa* and *A. taquetii* showed significantly higher chlorophyll and carotenoid contents in the contaminated soil than in non-contaminated soil, indicating that the tolerance mechanism to metal stress was activated at the seedling stage. Conversely, the lower content of the two pigments at harvest was attributed to long-term exposure to metal contamination. Total and available concentrations of HMs in soil did not alter during the cultivation. On the other hand, the concentration of HMs absorbed in plants varied with the plant species and the metal types. In general, *C. matsumurae*, *E. lindleyanum,* and *E. fortunei* showed a high capacity to absorb As, Cd, or Pb and accumulated them in the shoot parts, and the transfer factor, bioconcentration factor, and bioaccumulation factor related to this tended to be higher than those of other plant species. As a result of principal component analysis, native *E. lindleyanum* exhibited the highest efficiency in remediating Cd and As in HMs-contaminated soil, demonstrating strong plant performance and tolerance to metal stress.

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# Multidimensional approach to anthropogenic markers - evidence from urban soils in Krakow (SE Poland)

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**ABSTRACT**

Reconstructing the evolution of geochemical processes in cities is critical for soil protection and urban ecosystem management, and provides an environmental context for the historical development of urban space. Urban soils act as stratified archives in which technogenic inputs and natural sedimentary layers jointly record shifts in land use, industrial activity, fuel use, and building practices. This study applies a multidimensional approach to evaluate anthropogenic markers preserved in urban soils of Krakow (SE Poland) and to test whether independent proxies converge toward a coherent reconstruction of changing anthropogenic pressure.

Four profiles were excavated in representative urban settings down to horizons corresponding to sediments of a former riverbed. Each profile was described in detail (soil structure, texture, artefact abundance, and type) and sampled at high vertical resolution. We assessed a broad suite of anthropogenic proxies: (i) magnetic particles and magnetic properties, as indicators of high-temperature combustion and industrial emissions; (ii) technogenic components such as fragments of construction materials, slags/cinders and soot; (iii) mineralogical composition; (iv) bulk geochemistry for major and trace elements; (v) persistent organic pollutants; and (vi) selected isotope ratios to support source attribution where applicable.

The integration of field descriptions with magnetic, mineralogical, chemical, and isotopic information, therefore, yields an internally consistent multi-proxy record of increasing and changing human impact, consistent with successive phases of urbanization and industrialization. Beyond site-specific reconstruction, the dataset provides a basis for a critical appraisal of the sensitivity, robustness, and interpretative limits of individual anthropogenic markers in complex urban soil settings, supporting their informed use in urban soil classification, monitoring, and historical environmental analysis.

The design targets soil-science challenges where single indicators may be ambiguous. Magnetic and artefact-based proxies track particulate inputs and construction-related transformations, while mineralogical and isotopic information help separate lithogenic background, river-derived material, and anthropogenic additions. Using stratigraphic ordering, the profiles allow chronologies to be inferred and distinguish intervals dominated by combustion residues from phases of construction and backfilling. Together, these proxies improve the identification of technogenic horizons in soil archives.

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# Urban Soils of Nanjing City

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**ABSTRACT**

Nanjing is one of the old towns in China and dates back to more than 7000 years ago. Like other cities in China Nanjing grows very fast, from population of 2.6 million in the year 1949 to 9.6 million today. The urbanization rate is 87%. Nanjing has spread over the surrounding farmland and covers it by older and modern constructions. Different impacts of urbanization on soils can be observed. Soils of original horticultural and farmland has been changed to soils for urban use such as park areas, school yard, public lawn, roadside, between houses of residential areas constructed. Nanjing experienced the typical change of soil features by urbanization. In part the change differed between the older part and new construction areas of the city. The changes concerns the skeleton (stone) content, bulk density, pore volume and air and field capacity, pH value, carbonate, organic carbon, nitrogen, and phosphorus content, total stored organic carbon in soil profiles and C:N:P ratio. The changes of physical and chemical characteristics in urban soils will result in some environment problems. As a city with a long history, the formation of so-called cultural layers has special soil features, which can be used as a record of human activities. The urban soils in the old commercial, industrial and residential areas of Nanjing were generally with high organic and black carbon, as well as heavy metals, but their concentration levels varied significantly among the cultural layers formed in different dynasties. The studies of urban soil in Nanjing show new types of ecosystems which we have to learn to understand. The presentations will give some ideas what we can expect from soils.

**Keywords:** Urban soil; Soil genesis and evolution; Soil formation; Black carbon; Historical cultural layers

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# Urbanization Promotes Topsoil Black Carbon Accumulation: A Meta-analysis

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**ABSTRACT**

Accelerated urbanization underscores the importance of black carbon (BC) in urban soils, a key component of soil organic carbon with implications for ecosystem function and human health. This meta-analysis systematically integrated data from 54 studies comprising 4,548 sampling sites across 40 Chinese cities, supplemented by targeted field sampling, to examine the distribution, sources, and influencing factors of soil BC in urban environments. After rigorous screening, standardization, and outlier removal, correlation analysis and multivariate statistics were applied. Results showed an average urban topsoil BC content of 6.70 ± 5.34 g/kg, with marked spatial heterogeneity: higher concentrations were observed in eastern compared to western regions, and in northern relative to southern cities. Fossil fuel combustion—primarily vehicular emissions and industrial coal burning—was identified as the dominant source of BC, while biomass burning served as a secondary contributor, with additional local inputs from urban expansion and straw burning. Among natural factors, higher precipitation in southern regions enhanced BC migration, leading to reduced concentrations. Anthropogenic factors, however, exerted a stronger influence: cities with higher urbanization levels and greater energy consumption exhibited significantly elevated BC inputs. This study provides a comprehensive understanding of BC distribution patterns and source apportionment in China's urban soils, offering scientific support for urban environmental management and soil quality improvement amid ongoing urbanization, thereby contributing to sustainable urban development.

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# Underestimation of soil organic carbon by global spatially explicit soil datasets in Chinese urban greenspaces

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**ABSTRACT**

Soil organic carbon (SOC) in urban greenspaces can provide important ecosystem services for a large number of urban population around the world. However, the distribution, stocks, and drivers of SOC change in urban greenspaces are relatively unknown compared with those of natural ecosystems. To address this knowledge gap, we utilized 744 SOC measurements (0-30 cm depth) collected from urban greenspaces across 148 cities in China to investigate the key the distribution and drivers of surface SOC stocks (Fig.1).

Our analysis revealed weak correlations between in-field SOC measurements and estimates derived from widely used global SOC datasets (e.g., SoilGrids250m v2.0 and HWSD v2.0), underscoring the necessity for improved characterization of SOC distribution and its determinants in urban greenspaces (Fig.2). By employing Random Forest (RF) and SHapley Additive exPlanations (SHAP), we found that the enhanced vegetation index (EVI), mean annual precipitation (MAP), and social-economic status indicated by night-time light density (NLD) and population density (POP) were the most important predictors of surface SOC in Chinese urban greenspaces (Fig.3). RF model-predicted surface SOC in urban greenspaces was higher in moderately developed cities than in underdeveloped or highly developed cities. SOC increased with EVI, but displayed a hump-shaped trend with MAP, NLD, and POP. Spatial prediction of SOC stocks from the RF model showed that there were 0.21 (0.20-0.22, 95% confidence intervals) Pg C in the top 30 cm of soil in urban greenspaces of China (Fig.4), which was 17% and 50% greater than estimated by SoilGrids250m v2.0 (0.18 Pg C) and HWSD v2.0 (0.14 Pg C), respectively. Our study provides valuable data support and scientific guidance for carbon neutrality and urban greenspaces ecosystem management in China.



Fig. 1. Mapping (a), density distribution (b), regional overview (c), and urbanization gradient (d) of observed topsoil (0–30 cm depth) SOC concentrations (in g kg-1) in Chinese urban greenspaces.



Fig. 2. Scatter plots of observed topsoil SOC concentrations compared to SOC concentrations from (a) SoilGrids250m v2.0 and (b) HWSD v2.0 for Chinese urban greenspaces.



Fig. 3. Results of the Random Forest predicting SOC concentrations and SHAP analysis of predictors.



Fig. 4. The spatial pattern and uncertainty of predicted surface SOC concentrations (0-30 cm depth) in urban greenspaces of China.

# Upcycling Rare Earth Element Hyperaccumulator Biomass toward High-Performance Catalysts

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## ABSTRACT

Rare earth elements (REEs) are critical materials facing severe supply risks. Agromining, which uses hyperaccumulator plants to extract REEs from soils into harvested biomass, offers an eco-friendly alternative but is limited by the absence of efficient valorization pathways, since impurity cations complicate recovery. Here, we present an innovative strategy to directly upcycle biomass from the *Dicranopteris linearis*—rich in REEs, Al, and Si—into a high-performance biomass-derived REE catalyst (BioREOs) via a simple one-pot calcination (600 °C 2h ). The resulting BioREOs catalyst completely pyrolyzes polypropylene within 30 minutes at 400 °C, generating approximately 70% liquid oil with superior selectivity and efficiency compared to commercial REY catalysts. Mechanistic studies reveal that REEs within BioREOs stabilize an aluminosilicate framework, optimize Brønsted/Lewis acid site distribution, and promote selective β-scission while suppressing undesirable secondary cracking. We further identify potassium as a key interfering element that masks active acid sites, underscoring the importance of pre-removal. We demonstrate that directly upcycling REE-rich biomass into BioREOs catalysts exhibits a 2-fold increase in economic value and a 5-fold reduction in carbon footprint relative to conventional REY catalysts production, thereby establishing a commercially viable route for REE agromining through the valorization of both REEs and impurities.

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# Metabolic resilience of Allium cepa L. in urban technosols: the role of soil sealing and compaction on raffinose family oligosaccharides accumulation

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**ABSTRACT**

This study investigates the interaction between soil physical properties and the metabolic profile of onions (*Allium cepa* L.) cultivated in two distinct urban desealed sites in Ancona, Italy: Torrette and Vallemiano. Both sites were characterized by degraded technosols with high compaction and low organic content, treated with identical compost amendments. However, chemical analysis revealed a significant divergence in bulb composition: stachyose and raffinose were exclusively detected in onions from Vallemiano treated with compost, while being entirely absent in those from Torrette. These results are closely linked to the degree of soil sealing. In Torrette, the impermeable asphalt cover induced severe anoxic conditions, leading to a metabolic shutdown and preventing the energy-intensive biosynthesis of Raffinose Family Oligosaccharides (RFOs). Conversely, the degraded and heterogeneous surface at Vallemiano allowed for gas exchange and water infiltration. In this site, the combination of mechanical stress from fine-textured soils and chemical stress from secondary carbonates acted as an elicitor. Supported by the aerobic respiration permitted by the site's porosity, the onions utilized compost-derived nutrients to synthesize RFOs as essential osmoprotectants. These findings suggest that soil oxygenation is a prerequisite for the beneficial effects of organic amendments on plant resilience and that RFO accumulation serves as a bio-indicator of active metabolic adaptation in challenging urban environments.

**Keywords:** *Allium cepa* L., Technosols, Soil Sealing, Stachyose, Raffinose, Urban Agriculture, Plant Metabolic Stress.

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# Realising the value of urban soils

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**ABSTRACT**

Soils are the foundation of our urban environments but are rarely recognised for their multiple critical roles in climate regulation, flood control, local food production, connection of people to nature, and human health and well-being. Soil underpinning urban green spaces – particularly those with trees, are instrumental to delivering many of these benefits and the importance of urban soils is gaining greater attention internationally, for example, 'Healthy Soils for Healthy Cities' was the theme for World Soils Day 2025.

However, recognition of the value of urban soils is often overshadowed by the perception (and also the reality) of contamination from multiple anthropogenic activities. This focus on contamination, and sometimes overly precautionary approaches to its' management, can be key drivers for the unnecessary disposal of large volumes of soil to landfills. In New Zealand, soil was estimated to represent 87% of the 27.4 million tonnes of material disposed to landfills, including 'clean fills', in 2023 – highlighting also the significant opportunities for soil reuse.

In this presentation we outline three contrasting case studies from New Zealand that illustrate barriers and opportunities to realising different benefits of urban soils:

- Sustainable management of surplus soils (soils that have been disturbed through land and infrastructure development or natural processes – e.g. landslips, silt/sediment – and are unable to be beneficially used on-site)
- The nexus of 'background' soil concentrations, soil contaminant guideline values, waste acceptance criteria and the management of contaminated land and surplus soils
- The role of soil in increasing the 'sponginess' of cities to help manage and mitigate flooding events

We also draw on these case studies to identify key requirements for effecting improvements in urban soil quality as part of the development of a guide to regenerating urban soils.

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# Effect of solar panel installation on past agricultural soils

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**ABSTRACT**

The installation of solar panels is being promoted to increase the proportion of renewable energy sources in Japan's energy consumption. The installation requires civil engineering works on the ground, resulting in change in soil properties. Again, since the installed solar panel prevents solar radiation and rainfall on the ground, soil physico-chemical properties will be changed after the installation. This study investigated change in soil properties under and outside of the solar panels installed on past agricultural land. The soil under the solar panel installed previous paddy field has still kept mottles in the subsurface horizon with high Feo/Fed. However, the soil at the outside has no mottles and lower ratio of the secondary irons. Although the former soil was classified as Anthraquic Allophanic Andosols, the latter was Lowland Reformed Soils due to disappearance of mottles. Plants grow well on soils outside the solar panels due to taking rainfall and solar radiation compared to soils beneath the solar panels, resulting that lower available phosphorus and pH were recorded in the soils outside of the solar panels. Differences in the soil properties observed beneath and outside solar panels installed on upland fields cultivated for vegetables did not affect soil classification. The basement of solar panels also influences soil physical properties. Installation of solar panels using concrete block foundations makes land hard and difficult to reform the land. However, pile foundations influence on the ground with less damages, resulting in soft surface ground like as an agricultural field. Pile foundations are often used for solar panel installations that involve agricultural land uses. The future of field power stations using solar panels will increase anywhere in the world. However, power generation efficiency gradually declines due to dirt and degradation on the panel surface, potentially rendering it no longer worthwhile as compensation for land use. When the land use should be changed, the soil information is required. It is desirable to install solar panels in a manner that maintains the land in a condition suitable for conversion back to green spaces with productive soils.

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# Humate Boosts Liming value? Insights into humate-assisted lime dissolution across acidic environments

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## ABSTRACT

Subsurface soil acidity is a major constraint to agricultural production and remains difficult to ameliorate using conventional surface liming. A promising approach is to enhance the mobility of liming materials into the subsoil by increasing their solubility and reducing particle size, thereby promoting colloidal transport. Humic substances, particularly fulvic and humic acids contain diverse functional groups (e.g., carboxyl, amino, and hydroxyl) that may complex with calcium ($Ca^{2+}$) and facilitate the movement of lime-derived $Ca^{2+}$ and bicarbonate ($HCO_3^-$) into deeper layers, neutralizing acidity and increasing base cations. This study evaluated the effect of humate products on lime dissolution in acidic aqueous and soil systems. Potassium humate (K-humate), potassium fulvate (K-fulvate), and a fulvic-acid soluble powder were assessed for their influence on agricultural lime and dolomite dissolution over 14 days. An acidic sandy subsoil (10–20 cm) was used in the study. Dissolution was quantified by measuring increases in $Ca^{2+}$ and $Mg^{2+}$ concentrations in solution with ICP-OES. K-fulvate significantly enhanced lime dissolution in both aqueous and soil systems ($p < 0.001$). Non-linear Elovich model was well fitted ($r^2$=0.99) to Ca and Mg time-series data describing the kinetics of agriculture lime and dolomite dissolution in soil system over the 14-day period. Overall, dolomite dissolution in the soil system was more than double that in the aqueous system. This indicated that the humate products used in the study were not appreciably retained by the soil under experimental conditions and therefore did not inhibit their effect on lime dissolution, and facilitation of $Ca^{2+}$/$HCO_3^-$ movement into the subsoil. Additionally, the soil acted as a sink for dissolved ions, sustaining dissolution over time. Future work will include comprehensive evaluation of humate-amended lime on soil chemical properties and crop productivity.

**Keywords:** subsoil acidity; humate substances; dissolution kinetics; liming

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# The contribution of natural and anthropogenic causes to soil acidification rates under different fertilization practices and site conditions in southern China

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**ABSTRACT**

Excessive application of mineral fertilizers has accelerated soil acidification in China, affecting the production of crops when the pH drops below a critical value. However, the contributions of natural soil acidification, induced by leaching of bicarbonate, and anthropogenic causes of soil acidification, induced by nitrogen (N) transformations and removal of base cations over acid anions by crop harvest, under different fertilization management strategies, in particular considering the impact of land use, climate, and soil type are not well quantified. In this study, we quantified soil acidification rates, in equivalents (eq) of acidity, by assessing the inputs and outputs of all major cations and anions, including calcium, magnesium, potassium, sodium, ammonium, nitrate, bicarbonate, sulphate phosphate and chloride, for 13 long-term experimental sites in southern China. The acidification rates strongly varied among fertilizer treatments and with the addition of animal manure. In non-calcareous upland soils, the main driver of soil acidification was the overuse of nitrogen (N) and associated nitrate leaching. Reducing the N surplus decreased the acidification rate with 10 to 54 eq per kg N surplus with the lowest value occurring in paddy soils and the highest in upland soils. Natural bicarbonate leaching was the dominant acid production process in all calcareous soils (23 keq $ha^{-1}$ $yr^{-1}$) and in non-calcareous paddy soils (9.6 keq $ha^{-1}$ $yr^{-1}$), accounting for 80% and 68% of total acid production rate, respectively. The calcareous soils were strongly buffered, and acidification led to a decline in calcium carbonate levels but with no or a limited decline in pH. In contrast, N transformations were the most important driver for soil acidification in upland crops on non-calcareous soils, accounting for 72% of total acid production rate of 8.4 keq $ha^{-1}$ $yr^{-1}$. In these soils, the soil pH considerably decreased being accompanied by a substantial decline in exchangeable base cation. The use of manure, containing base cations, partly mitigated the acidifying impact of N fertilizer inputs and crop removal, but enhanced phosphorus (P) accumulation. Combining mineral fertilizer, manure and lime in integrative management strategies can mitigate soil acidification and minimize N and P losses.

**Keywords:** Mineral fertilizer, manure, acid production, acid consumption, acidification

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# Sensitivity of Soil Organic Matter Priming to Warming Depends on Diurnal Temperature Cycle

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**ABSTRACT**

Understanding soil organic matter (SOM) mineralization is critical for predicting soil carbon (C) cycling, yet the effects of diurnal temperature fluctuations and their interactions with labile C inputs remain unclear. Acidic arable soils were incubated for 42 days under constant temperatures (15 or 25 °C) or diurnal temperature fluctuations, without or with $^{13}$C-glucose addition. Diurnal fluctuations enhanced cumulative SOM mineralization and priming effects, with a higher temperature sensitivity ($Q_{10}$) of priming (2.6) than constant temperatures (2.4). The higher $Q_{10}$ was associated with an increased response of C-degrading enzyme activities to warming. At the community level, fungal diversity declined with warming, particularly under diurnal fluctuations. Although microbial networks were restructured, their topology exerted little influence on SOM mineralization. Instead, fungal diversity and cellobiohydrolase activity were the primary drivers of variation in SOM mineralization and its $Q_{10}$. These findings provide mechanistic insights into acidic soil C cycling under climate change, emphasizing the importance of incorporating daily temperature fluctuations into predictive models.

*This ABSTRACT is based on work that has been previously published in J. Agric. Food Chem., 2025. The submitted ABSTRACT summarizes the key findings for presentation purposes only.*

# Biochar Mitigates the Kinetic Release of Aluminum from Soil Driven by Exogenous Acid

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## ABSTRACT

The release of solid aluminum (Al) in soil, induced by exogenous acid, is the primary factor limiting crop growth in acidic soils. Biochar has been demonstrated to reduce the concentration of active Al in soil under equivalent acid input. However, the dynamic mechanisms by which it mitigates Al release remain unclear. A stirred-flow dynamic acidification experiment was conducted to comparatively analyze the kinetic processes of solid-phase Al release in soils amended with biochar and lime. The results indicate that the release of Al from each treated soil exhibits distinct stage characteristics during the acidification process: an initial phase with acceleration, a subsequent phase of deceleration, and a final phase with uniform speed. These stages can be accurately fitted using piecewise functions representing first-order dynamics, pseudo-first-order dynamics, and linear equations ($R^2$ >0.999). The fitting results suggest that the three stages are governed by proton diffusion, potential active Al diffusion, and solid-phase Al dissolution, respectively. At the end of the reaction, the cumulative release of Al from soil amended with biochars was 8.98% ~17.23% lower than that in soil amended with lime. This reduction primarily occurred at the early and middle stages of acidification. In the initial stage, biochar competes for $H^+$ by protonation of surface organic functional groups, thereby inhibiting $H^+$ involvement in the Al release reaction. Concurrently, biochar reduces the diffusion rate constant of $H^+$ in soil through its porosity, collectively decreasing the solid Al release rate. In the middle stage, both peanut straw biochar and rice straw biochar significantly decreased the soil Al diffusion rate constant, with reductions ranging from 20.29% to 62.75%. Notably, rice straw biochar also resulted in a 17.84% reduction in the potentially active Al content in the soil. Consequently, the effect of rice straw biochar in slowing down the release rate of soil Al was superior to that of peanut straw biochar during the middle stage of acidification. In the later stage of acidification, the release rate of soil Al was not affected by biochar. Biochar enhances the kinetic stability of solid Al release in acidified soils by improving soil pH buffering capacity, reducing the potential active Al content, and optimizing soil pore structure. These findings offer a theoretical foundation and technical support for the long-term prevention and management of Al toxicity in acidic soils.

**Key words:** Soil acidification; Biochar; Lime; Aluminum release; Kinetics

**Acknowledgments**

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# Diverse organic amendments mitigate soil acidification and enhance crop productivity in acid soil area over four decades

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## ABSTRACT

Organic amendments, e.g., livestock manure, straw, green manure, have shown profound performance to enhance soil carbon (C) sequestration and crop productivity. However, despite extensive research on their individual benefits, the synergistic effects of combining plant-derived C and livestock manure inputs on soil pH buffering capacity (pHBC)-the key determinant that governs proton neutralization and reflects the soil long-term resistance to acidification. In the present study, based on a 42-year ongoing field experiment, we explored the response of pHBC and crop productivity to synergistic incorporation of plant-derived C input (green manure, green manure combined with straw) vs. diverse-derived C input (livestock manure combined with plant-derived C input) from various organic amendments. Mineral fertilization caused pH decline by 0.12-0.39 units, compared with diverse-derived C input. Plant-derived C input showed no significant effect on pHBC either after three or four decades versus control. However, the diverse-derived C input, e.g., synergistic incorporation of green and livestock manure, increased soil pHBC by 31-40% compared with control. This improvement was primarily attributed to increases in exchangeable $Ca^{2+}$ and the accumulation of soil organic matter (SOM), particularly humic substance compositions. Furthermore, the protonation of organic anions released during humic acid dissociation provided abundant proton-binding sites under diverse-derived C input, thereby enhancing the soil's intrinsic pH buffering capacity and strengthening its resistance to further acidification. In addition, the exchangeable $Al^{3+}$ was decreased by 67%-88% with diverse-derived C input, relative to control. This was due to the accumulation of humic acids promotes Al-organic complex formation, consequently reducing the exchangeable $Al^{3+}$ in soil solution. The increase in Alp content under diverse-derived C input also confirmed that. Critically, the mitigation of soil acidification establishes a critical foundation for improving crop yields, average outperforming control and plant-derived C input by 32% and 12%, respectively. These findings highlight that the diverse-derived C input based on soil amendments as agronomically optimal and environmentally sustainable strategy to mitigate soil acidification and sustain crop productivity in acid soil area.

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# Co-application of lignosulfonate and calcium–magnesium phosphate fertilizer, an effective liming strategy for acidic purple soils in southwest China

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**ABSTRACT**

Purple soils in southwestern China are facing the dual challenges of soil acidification and declining fertility. Particularly, the accumulation of phytotoxic exchangeable aluminum ($Al^{3+}$) and the reduction of available phosphorus, which respectively promote the leaching of base cations and constrain crop growth, collectively constitute a substantial threat to soil health and food security. The disadvantages and high costs associated with amendment lime highlights the need for alternative soil amendments. Here, we demonstrate an efficient co-application strategy using a base ion-enriched organic amendment, calcium lignosulfonate, in combination with calcium–magnesium phosphate fertilizer to ameliorate acidic purple soils (Figure 1). During the maize growing season, this co-application of 1 wt% calcium lignosulfonate and 1 wt% calcium–magnesium phosphate fertilizer increased soil pH by 0.32–1.16 units, reduced exchangeable $Al^{3+}$ by up to 88%, and enhanced soil organic matter and available phosphorus contents by 24–35% and 142%, respectively. These improvements translated into substantial agronomic benefits, with maize yields increasing by 62–176% compared with unlimed soil conditions. Molecular modeling revealed that the functional groups of calcium lignosulfonate exhibit strong competitive adsorption of $Al^{3+}$ ions over base cations and facilitating the formation of stable $Al^{3+}$–sulfonate precipitates (Figure 2). Moreover, the co-application restructured beneficial microbial communities and enhanced functional genes involved in soil carbon and phosphorus cycling (Figure 3). These amendments not only promoted soil organic acids and ABC transporters to enhance the immobilization and detoxification of exchangeable $Al^{3+}$, but also increased available phosphorus and enzyme activities to alleviate phosphorus limitation. Collectively, these physicochemical and microbial improvements indicate that the co-application of calcium lignosulfonate and fused calcium–magnesium phosphate fertilizer represents an economically viable and sustainable strategy for detoxifying phytotoxic exchangeable $Al^{3+}$, enhancing the fertility of acidified purple soils, and safeguarding soil health and food security.

**Keywords:** Acidic purple soil, Corn, Calcium lignosulfonate, Exchangeable $Al^{3+}$, Molecular dynamics simulation

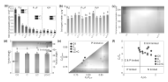


Figure 1. Panels (a–c) illustrate the changes in soil properties following the application of amendments. Panels (d–f) present the enzymatic stoichiometry associated with relative carbon, nitrogen, and phosphorus acquisition.

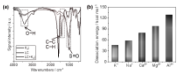


Figure 2. (a) Fourier transform infrared spectra. (b) Dissociation energies of cations bound to the surface functional groups of calcium lignosulfonate.

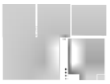


Figure 3. Microbial communities in acidic soil without (a) and with (b) the application of soil amendments. (c) Correlations among functional genes, environmental factors, and microbial taxa. (d) Correlations between functional genes and microbial taxa. (e) Interactions between calcium lignosulfonate and soil enzymes.

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# Building a Stable Mineral–Microbial Buffering System for $Al^{3+}$ Detoxification and Productivity Recovery in Acidified Purple Soils

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## ABSTRACT

Rapid acidification of purple soils in southwestern China severely threatens crop productivity by intensifying exchangeable acidity, accelerating base-cation depletion, and inducing phytotoxic $Al^{3+}$ stress. High costs and limited persistence of conventional lime underscore the need for practical and scalable alternatives. Here, we demonstrate that the co-application of calcareous parent rock powder (M) and a self-selected acid-suppressing bacteria (H) provides a highly effective strategy for restoring acidified purple soils during maize cultivation. The combined M+H treatment markedly improved soil chemical properties, elevating soil pH to 5.14–5.17, reducing exchangeable acidity by more than 80%, and doubling exchangeable base cations compared with the untreated control. Soil available P and rapidly-available K increased to 80–85 mg $kg^{-1}$ and 12 mg $kg^{-1}$, respectively, accompanied by enhanced carbonate buffering and cation exchange capacity. These benefits translated into substantial agronomic gains, with maize root biomass, total biomass, and hundred-grain weight increasing by 60–120%, 90–110%, and 150–200%, respectively. Importantly, the M+H synergy also restructured beneficial microbial communities and strongly stimulated the expression of ABC transporters and functional genes associated with organic acid metabolism, P mobilization, and $Al^{3+}$ detoxification. These microbial enhancements accelerated the immobilization and detoxification of phytotoxic exchangeable $Al^{3+}$, forming a stable soil–mineral–microbial buffering system that sustains long-term soil fertility improvement. Collectively, these findings highlight that the co-application of calcareous parent rock powder and acid-suppressing microbes represents an innovative, low-cost, and scalable solution for mitigating $Al^{3+}$ toxicity, rebuilding fertility, and enhancing crop productivity in acidified purple soils—offering substantial potential for improving regional soil health and agricultural resilience.

**Keywords:** Acidic purple soil, Calcareous parent rock, Acid-suppressing bacteria, Corn

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The authors thank the Ministry of Agriculture and Rural Affairs of the People's Republic of China for funding this project.

# Microbial driven soil carbon cycling in red soil aggregates under different fertilization

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**ABSTRACT**

Dissolved organic matter (DOM), as a sensitive indicator reflecting changes in the soil organic carbon pool, its characteristic variations and driving factors has long been a research focus worldwide. The incorporation of organic amendments such as crop straw into agricultural soils influences both the quantity and composition of soil DOM, thereby regulating organic carbon turnover and playing a pivotal role in terrestrial ecosystem carbon cycling. The decomposition and transformation of returned straw into soil DOM constitute is a highly complex process involving chemical, physical, and biological interactions. These processes are governed by multiple factors including environmental conditions, intrinsic properties of the straw, and microbial activity. Soil aggregates serve as crucial protective microenvironments for soil organic matter; at the same time, their formation is closely linked to the effects of organic matter and microbial transformations. Consequently, elucidating how soil microorganisms drive organic matter transformation at the aggregate scale is of great significance for understanding the mechanisms underlying soil carbon sequestration. Our study investigated how combined organic-inorganic fertilization influences the molecular characteristics of dissolved organic matter (DOM) within different soil aggregates and its interaction with bacterial communities. This long-term experiment evaluated the effects of five treatments: a no-fertilizer control (CK), chemical fertilizer alone (NPK), and NPK in combination with straw (NPKS), straw and manure (NPKSM), or straw-derived biochar (NPKSB). Soil was fractionated into large (LMA), small (SMA), and micro-aggregates (WMA) for analysis. Results showed that the NPKSM treatment increased the aromaticity and nominal oxidation state of DOM in LMA and SMA, but decreased them in WMA. It promoted the accumulation of recalcitrant compounds like lignin and tannins in macro-aggregates, driven primarily by thermodynamically favorable processes. The transformation of DOM components increased by 3.77%-34.94% in these aggregates. Bacterial community analysis revealed that microbes in SMA tended to synthesize DOM and exhibited stronger collaboration, particularly through interactions between lignin and Acidobacteriota, which enhanced carbon sequestration. This research clarifies the microbial-mediated mechanisms of soil carbon cycling in red soil aggregates under different fertilization.

**Acknowledgments**

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# Mycorrhiza-Mediated Soil Aggregate Stability under Maize//Soybean Intercropping in Acid Soil

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## ABSTRACT

Mycorrhizae play an important role in mediating soil aggregate formation. Intercropping can influence rhizosphere mycorrhizae , but the mycorrhiza-mediated effects and mechanism on soil aggregates in intercropping system remains unclear. This study aims to investigate the effects of maize//soybean intercropping on soil aggregate stability and the mycorrhiza-mediated mechanism in acid soil under intercropping.

**Methods:** Based on a 7-year continuous field positioning experiment, two planting patterns: maize monoculture (MM) and maize//soybean intercropping (MI) were compared under four phosphate application rates (P0, P60, P90, P120, corresponding to 0, 60, 90, 120 kg $P_2O_5$ $ha^{-1}$, respectively), the effects of maize//soybean intercropping on mycorrhizal colonization, glomalin content, soil aggregate composition, and stability were analyzed.

**Results:** The results showed that, maize//soybean intercropping significantly improved soil aggregate atability and mycorrhizal colonization. Under different phosphate application levels, compared to the corresponding monoculture, maize // soybean intercropping increased the soil macroaggregate content by 11.48%,the mean weight diameter(MWD) average increased by 5.35% ,and the geometric mean diameter (GMD） average ncreased by 6.72%. The mycorrhizal colonization rate, hyphal density and spore density of intercropped maize average increased by 33.2%,30.7% and 29.15%, respectively. The easily extractable glomalin(EEG) and total glomalin (TG)average increased by 23.49% and 20.22%, respectively. Random Forest model analysis indicated that, soil macroaggregate content contributed the most to soil aggregate stability, while the important contributing factors affecting soil macroaggregate content were, in order: total glomalin, easily extractable glomalin, hyphal density, mycorrhizal colonization rate, and spore density. Structural equation modeling further revealed that maize//soybean intercropping enhanced the content and proportion of macroaggregates in red soil by increasing mycorrhizal colonization and glomalin content, thereby promoting the stability of red soil aggregates.

In conclusion, maize//soybean intercropping mediated the formation and stabilization of soil aggregates by significantly stimulating the mycorrhizal colonization and their secretion of glomalin, thereby improving soil structure and ultimately promoting increased crop yield.

**Keywords:** Maize//soybean intercropping; Arbuscular mycorrhizal; Glomalin-related soil protein; Soil aggregate stability; Acid soil

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This study was supported by the National Key Research and Development Program of China ( 2022YFD1901503) and the National Natural Science Foundation of China (32260805).

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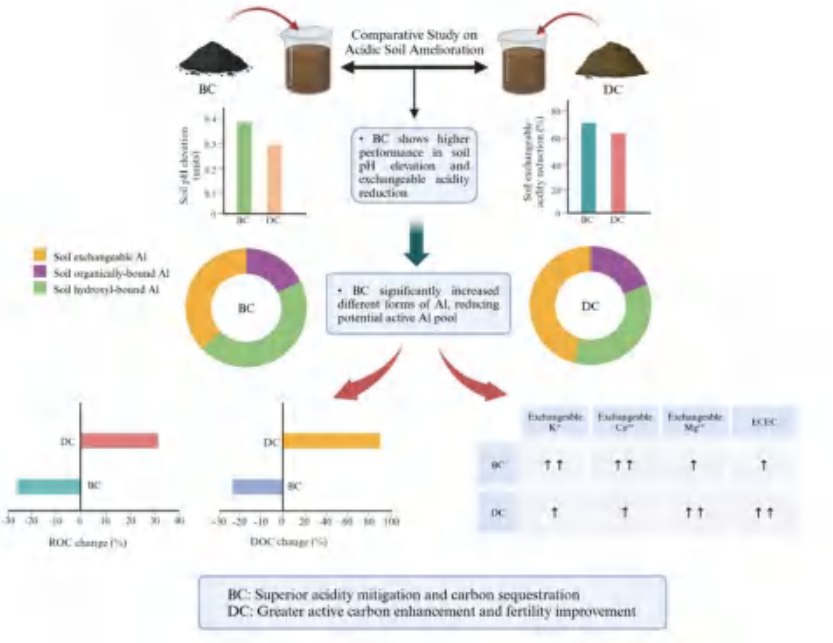
# Synergistic effects of Rice Straw-Pyrolyzed Biochar and Com-post on Acidity Mitigation and Carbon Sequestration in Acidic Soils: A Comparative Study

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## ABSTRACT

Biochar and compost derived from straw present synergistic effects on acidity mitiga-tion and carbon sequestration in acidic soil, however, the differential synergistic effects and mechanisms remain poorly understood. This study investigates the comparative effectiveness of rice straw biochar (BC) and compost (DC) on acidic soil amelioration through an incubation experiment. BC demonstrated superior performance in soil pH elevation (0.39 vs. 0.28 pH units) and exchangeable acidity reduction (69% vs. 62%) due to higher alkalinity (148.51 vs. 115.73 cmol $kg^{-1}$) than DC. Additionally, BC decreased soil potential active Al pool more than DC (35.1% and 25.2%) through promoting hy-drolytic precipitation. Carbone fractions analysis showed that BC enhanced soil or-ganic carbon more effectively (83.7% vs. 64.0%), it reduced ROC (27.6%) and DOC (24.0%), contrasting with DC's increases (31.6% and 93.8%, respectively). The contrary effect was attributed to BC's lower active carbon content, higher alkalinity, and C/N ratio. Both amendments improved soil fertility, with BC and DC increasing ex-changeable $K^+$ (14.0 vs. 12.3 times), $Ca^{2+}$ (5.4 vs. 4.9 times), $Mg^{2+}$ (3.7 vs. 5.2 times), and ECEC (11.8% vs. 15.2%). These findings demonstrate BC's superior acidity mitigation and carbon sequestration, while DC shows greater active carbon enhancement and fertility improvement.




**Keywords:** Acidic soil; Straw-derived biochar; Straw-derived compost; Alu-minum immobilization; Soil organic carbon

**Acknowledgments**
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# Mechanisms for Plants to Adapt to Toxicities of Aluminum and Manganese in Acidic Soil/Root Interfaces

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## ABSTRACT

Soil acidification leads to the activation of solid-phase aluminum (Al), and the toxicity of Al and manganese (Mn) in acidic soils is the primary cause of poor plant growth and reduced yields of crops in such soils. When plants are subjected to Al stress in acidic soils, their root systems actively secrete low-molecular-weight organic acids into the rhizosphere soil solution. These organic acids form low-toxic or non-toxic Al-organic acid complexes with the active Al in the soils, thereby mitigating Al toxicity. This is the primary mechanism by which plants adapt to Al stress in acidic soils. Recently, we discovered a novel mechanism by which a plant adapts to Al and Mn toxicity in acidic soils. When plants are subjected to the stresses of Al and Mn, their roots produce fewer surface functional groups and surface negative charges, thereby reducing the adsorption of $Al^{3+}$ and $Mn^{2+}$ by the roots and alleviating the toxicity of these two cations to the roots. In hydroponic experiments, when rice grows in a nutrient solution containing Al and $NH_4^+$, the rice absorbs $NH_4^+$ and releases $H^+$ into the nutrient solution through its roots, which leads to a decrease in the pH of the nutrient solution, and should enhance the toxicity of Al to rice roots. However, Al causes less damage to rice roots growing in nutrient solutions containing $NH_4^+$ than those growing in nutrient solutions containing Al and $NO_3^-$. The measurements of zeta potential and infrared spectroscopy of rice roots showed that the number of functional groups and negative charges on rice roots grown in $NH_4^+$ nutrient solution was lower than that of rice roots grown in $NO_3^-$ nutrient solution, and the adsorption capacity of rice roots for $Al^{3+}$ and $Mn^{2+}$ was also lower in the former than in the latter, providing experimental evidence for the above mechanism. Similar hydroponic experiments were conducted on corn, soybeans, and wheat, and similar experimental phenomena were observed, indicating that these plants have the same mechanism of adaptation to Al and Mn toxicity. Adjusting the pH of a red soil to 4.5 and 6.5 respectively, and then conducting pot experiments on these plants, it was found that the number of functional groups and negative charges on the roots of plants grown in pH 4.5 red soil was lower than those grown in pH 6.5 red soil, indicating that plants use the above mechanism to alleviate the toxicity of Al and Mn in acidic soils. Further research indicated that D-galactose, malate and trehalose were critical regulators of hemicellulose biosynthesis and cell wall remodeling of plant roots. Al stress downregulated D-glucosamine metabolism while upregulating cutin/suberin/wax components docosanoic acid and 22-hydroxydocosanoate. This shift reduced synthesis of hemicellulose, inhibited cell wall assembly enzymes, and thus decreased cell wall negative charge and anionic oxygen-containing functional groups.

# Incorporating lime into acidic subsoil improved root growth and rhizosphere microbial activity in wheat

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## ABSTRACT

Soil acidification is a widespread problem threatening sustainable crop production in many agricultural regions worldwide. In Western Australian agricultural regions, 70% of surface soils and approximately 50% of subsurface soils are below the target pH ($CaCl_2$) for optimal crop growth. Lime application is one of the common practices to improve soil acidification, as it neutralizes soil acidity, raises pH, and enhances nutrient availability. However, the movement of lime from topsoil to subsoil is slow, leaving the deeper soil layers in unfavorable conditions for crop growth. Recent research demonstrates the potential role of rhizosphere microbes in the mitigation of environmental stress. However, how soil re-engineering with lime affects soil microbial communities is poorly understood. We used acidic subsoil (pH4.6 in $CaCl_2$, 10–40 cm) and neutral topsoil (0–10 cm) collected from a farm in Grass Valley (31.40°S, 116.41°E) in the wheatbelt region of Western Australia Grass Valley, Western Australia, to re-construct soil profiles into 40-cm deep PVC columns after air-died and sieved. The subsoils were amended with lime (1 g $kg^{-1}$ soil). Half of the soils were steam sterilized to compare microbial activity. Wheat plants were assessed at the tillering and milking development stages for analyses of root morphology, photosynthetic performance, soil pH, and microbial biomass carbon (MBC). Results revealed that lime application significantly enhanced microbial biomass in the subsoil during the milking stage. Moreover, there was lime × sterilization interaction in the pH in both topsoil and subsoil at both growth stages. Sterilization significantly increased intercellular $CO_2$ concentration (Ci) and stomatal conductance (Gs). Principal component analysis demonstrated that soil re-engineering promoted subsoil root proliferation in the presence of active microbial communities at the tillering stage. During the milk development stage, soil re-engineering and active microbial presence greatly enhanced canopy greenness, photosynthetic activity, and color saturation. In conclusion, soil re-engineering with lime significantly improved soil pH in subsoil, promoted wheat growth, and microbial activities in the subsoil. In return, improved soil microbial activities promoted root growth in the subsoil through altering root morphology, regulating stomatal behavior, and enhancing canopy photosynthetic performance and color vitality.

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# Spatio-temporal Variation Characteristics and Driving Mechanisms of Soil pH in Farmland of the Changbai Mountain–Liaodong Region

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**ABSTRACT**

Soil acidification impacts regional food security and the sustainable development of agricultural systems. To formulate and implement targeted measures for preventing and mitigating acidification in farmland soils, it is essential to clarify regional soil pH heterogeneity and its influencing factors. This study, based on a comparison of 6,428 pairs of surface soil pH data collected at identical locations in the Changbai Mountain–Liaodong region in 1984 and 2024, elucidates the spatial variability characteristics of agricultural soil acidification in this area and its influencing factors. Results indicate that over the past four decades, the mean surface soil pH in the Changbai Mountain–Liaodong region has decreased by 0.5 to 1 pH units. Over 90% of farmland exhibits varying degrees of acidification, with the phenomenon showing a trend of expanding from localised areas to broader zones and progressing from mountainous to hilly terrain. Notably, the rate of acidification intensified significantly more between 2010 and 2024 than during the preceding decade from 1980 to 2010. Changes in the surface pH of agricultural soils are closely linked to factors such as climate, atmospheric deposition, topography, and inherent soil properties, reflecting multi-level coupling mechanisms under complex environmental conditions.

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# Acidification Discrepancy in Soils with Contrasting Surface Charge

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**ABSTRACT**

Soils are classified as Permanent charge soil (PCS) and Variable charge soil (VCS). However, the distinct acidification responses in the two soil types are still unclear. This study aimed to clarify the mechanism of ion exchange reactions governing soil acidification and their differences in PCS and VCS, and provide specific and tailored practices for acidification amendment of croplands with different surface charge properties. The release of ions and basic properties of two PCS (PCS-QX, PCS-XC) classified as cambisols and two VCS (VCS-QY, VCS-ML) classified as Typic Hapludults after soaking in acid were determined. The results indicated that the release of calcium ions ($Ca^{2+}$) and magnesium ions ($Mg^{2+}$) in PCS was higher than in VCS; conversely, the release of aluminum ions ($Al^{3+}$) in PCS was lower than in VCS. Both PCS and VCS showed the same patterns in the release of potassium ions ($K^{+}$) and manganese ions ($Mn^{2+}$), following the sequence of VCS-QY > PCS > VCS-ML. Moreover, the release of iron ions ($Fe^{2+}$) in the two soil types was extremely low. The release of $Al^{3+}$ in PCS was best described by the Elovich equation, indicating that the surface reactions governed it; conversely, VCS was best described by the parabolic diffusion equation, indicating that the intragranular diffusion governed it. Across all soil types, the release of $Ca^{2+}$ and $Mg^{2+}$ was best described by the two-constant rate equation, indicating complex release mechanisms. The release of $K^{+}$ and $Mn^{2+}$ was best described by the Elovich equation and the parabolic diffusion equation, respectively, which was attributed to the specific adsorption of $K^{+}$ and the reduction dissolution process of manganese oxide, respectively. In summary, the acidification of PCS is primarily governed by non-pH-dependent cation exchange processes, whereas pH-dependent surface charge alterations and mineral dissolution dominate that of VCS. As a result, improving PCS acidification should focus on replenishing base cations, whereas improving VCS requires fundamentally increasing its negative charge and reducing aluminium toxicity through the application of organic fertilisers to raise pH levels. Future research should focus on the distinct acidification mechanisms and behaviors in surface properties between PCS and VCS.

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# Effect of Intermittent Irrigation on Rice Growth and GHG Emission in Rice Paddies on Acid Sulfate Soils

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Keywords: Acid sulphate soil, Climate change mitigation, Rice paddy, Nutrient cycling

## ABSTRACT

Since the adoption of the Paris Agreement in 2015, climate change mitigation has become an urgent global issue, and agriculture is a major source of methane ($CH_4$) and nitrous oxide ($N_2O$) emissions (FAO, 2021b; Gütschow et al., 2021; Saunois et al., 2020). Rice, the staple food for nearly half of the world's population, is mainly produced in Asia (FAOSTAT, 2024). However, flooded paddy fields emit $CH_4$ due to methanogenic activity under anaerobic conditions. Intermittent irrigation is an effective strategy for reducing $CH_4$ emissions, but temporary soil drying may alter the dynamics of other soil constituents. In Asian coastal regions, acid sulfate soils (ASS) are widely distributed and may inhibit rice growth under alternating flooding and drainage due to soil acidification. With increasing food demand, the utilization of marginal soils such as ASS is expected to expand, highlighting the need for rice cultivation practices that ensure stable yields with reduced environmental impacts.This study aimed to identify the optimal drainage intensity of intermittent irrigation that reduces greenhouse gas emissions (GHG) from ASS paddy while maximizing rice yield.

A pot experiment was conducted using soils collected from Ogata Village, Akita Prefecture (OG), Inashiki City, Ibaraki Prefecture (IN), and a research field at Hachimandai (HM) as a control. Three water management treatments were applied: continuous flooding (CF), moderate intermittent irrigation (MD), and intensive intermittent irrigation (PL). The rice cultivar IR64 was used. GHG fluxes were measured using the closed chamber method, and $CH_4$ and $N_2O$ concentrations were analyzed by gas chromatography. After harvest, rhizosphere growth, yield components, and basic soil physicochemical properties were evaluated.

Soil pH ($H_2O/H_2O_2$) values were 7.35/5.08 for OG soil and 4.23/3.52 for IN soil, which did not meet the criteria for sulfuric acidity. However, the low pH($H_2O_2$) of IN soil suggested the presence of pyrite ($FeS_2$). Available phosphorus contents were similar between OG and IN soils, whereas calcium content was much higher in OG soil (32.85 cmolc $kg^{-1}$) than in IN soil (3.49 cmolc $kg^{-1}$), possibly due to shell-derived calcium before land reclamation. Under CF conditions, post-harvest rhizosphere growth was highest in HM soil, followed by OG and IN soils. In contrast, rhizosphere growth in IN soil improved under MD and PL conditions compared with CF, suggesting suppression of hydrogen sulfide ($H_2S$) production by intermittent irrigation. Grain dry weight and aboveground biomass were consistently lower in IN soil across all treatments. Aboveground biomass was highest under CF in HM and OG soils, whereas it was highest under PL in IN soil.

Moderate intermittent irrigation in ASS paddy can suppress $H_2S$ production and improve rice growth and yield, while also tending to reduce $CH_4$ emissions. Further analysis is ongoing to clarify soil–water management interactions.

# Liming regulates MAOC-POC trade-offs in paddy soils through a coupled mineral-microbial mechanism

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## ABSTRACT

Excessive application of chemical fertilizers has accelerated soil acidification in paddy soils of southern China, reducing rice productivity once pH falls below a critical threshold. Liming is widely used to raise soil pH, yet how different lime materials regulate soil organic carbon (SOC) fractions via microbe–mineral interactions remains poorly understood. Here, we conducted a controlled incubation experiment to quantify how contrasting lime materials influence SOC fractionation and stabilization in paddy soils. Increasing pH systematically redistributed SOC among fractions: higher pH enhanced cation bridging and favored the accumulation of mineral-associated organic carbon (MAOC), a relatively stable pool important for long-term carbon storage. In contrast, elevated pH weakened Ca-mediated bonding within particulate organic matter, leading to pronounced losses of particulate organic carbon (POC), a more labile pool that supports short-term nutrient supply. Microbial communities responded differentially across treatments. Fungi increased strongly with rising pH, whereas bacterial responses were constrained by threshold effects, together increasing the fungal-to-bacterial ratio. This shift in microbial dominance redirected carbon turnover from rapid, broad-substrate decomposition toward a strategy prioritizing the degradation of more recalcitrant carbon, producing a "quality increase, quantity decrease" pattern in the SOC pool. Integrating mineral and microbial evidence, we showed that SOC stabilization was constrained to a narrow pH window (5.5-6.5) governed by two coupled mechanisms: a "mineral adsorption threshold" that limits additional MAOC formation and a "microbial metabolic switch" that alters decomposition pathways, with $Ca^{2+}$ acting as a key fine-tuning agent. Maintaining paddy soils within this optimal pH range may therefore help balance the trade-off between long-term carbon sequestration (MAOC) and the active carbon pool (POC) that sustains soil biological activity, fertility, and crop production.

# Straw return exacerbates soil acidification in major Chinese croplands

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**ABSTRACT**

Soil acidification in croplands is a worldwide problem threating grain production and agricultural sustainability. Straw return has been widely recommended as a practice of climate-smart agriculture. It is generally believed that straw return also helps to alleviate soil acidification, while this assumption has not been tested over large geographical areas. Here, we assess its contributions to soil acidification based on three datasets across China. Unexpectedly, we found straw return predominately aggravated soil acidification in 145 investigated field experiments. The magnitude of straw-induced soil pH change was negatively correlated with the initial soil pH. Based on data from a national soil survey, we estimated that straw return would exacerbate soil acidification in 77% and 80% of dry and paddy lands, respectively. Our analysis disclosed the first evidence of accelerated soil acidification by straw return at national scale, providing new insights into both sustainable straw utilization and soil acidification remediation.

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# Mechanisms of periphyton-induced carbonate precipitation and its role in regulating soil acidity in paddy soils

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## ABSTRACT

In pursuit of carbon neutrality, microbially induced carbonate precipitation has emerged as a promising technology for inorganic carbon sequestration. However, existing research has predominantly focused on single bacterial strains, with little attention paid to natural microbial aggregates such as periphyton. As a primary microbial community at the sediment–water interface, periphyton consists largely of photoautotrophic organisms. Our results demonstrate that periphyton is highly effective in inducing carbonate precipitation, primarily by raising the suspension pH above 9 through photosynthesis under light conditions, and secondarily via urease hydrolysis. For instance, in suspensions with an initial pH of 7.0, 2.5 mM $Ca^{2+}$, and 7.5 mM or 15 mM $NaHCO_3$ under light exposure, periphyton achieved $Ca^{2+}$ precipitation ratios of 72% and 97%, respectively. In contrast, no precipitation occurred under dark conditions. These effects were enhanced by stronger light intensity and higher $Ca^{2+}$ or $HCO_3^-$ concentrations. Additionally, the active pumping of $Ca^{2+}$ through ion channels and its extracellular concentration of $Ca^{2+}$ further promoted calcium carbonate precipitation. Thus, periphyton drives calcium carbonate precipitation through synergistic mechanisms, with approximate contributions of 38% from photosynthesis, 24% from urease hydrolysis, and 31% from microbial-mediated extracellular $Ca^{2+}$ pumping. In contrast, extracellular polymeric substances of periphyton reduced precipitation by adsorbing $Ca^{2+}$, thereby diluting its availability. Periphyton is also widespread on paddy soil surfaces. When established on such soils, it can raise the pH of acidic soils and their suspensions, and inducing calcium carbonate precipitation in alkaline soils. Therefore, periphyton holds significant potential for inorganic carbon sequestration and mitigation of soil acidification. These findings provide a theoretical foundation for developing periphyton-based strategies to address global climate change and soil acidification.

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# Synergistic Amelioration Effects of Dolomite-Based Composite Conditioner on Soil Acidification: Mechanisms and Long-Term Buffering Performance

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**ABSTRACT**

Soil acidification is a major constraint to global agricultural sustainability, and the progressive decline in soil buffering capacity further weakens soil resilience to acid inputs, creating a self-reinforcing cycle of accelerated degradation. Conventional soil conditioners can temporarily neutralize acidity but fail to enhance intrinsic buffering capacity or maintain long-term pH stability. In this study, a composite soil conditioner, GL/ND/BC/MMT, was prepared by chemically cross-linking gelatin (GL), dolomite (ND), biochar (BC), and montmorillonite (MMT). The incorporation of glutaraldehyde produced a three-dimensional gelatin network designed to enable controlled release of pH-buffering components. Porous structure was clearly observed by SEM, whereas FT-IR characterized the chemical composition and cross-linking within the composite. A series of acidification, moisture retention, soil incubation, and crop growth experiments demonstrated that GL/ND/BC/MMT exhibits superior buffering performance within pH 4.0–5.5, effectively resisting rapid pH decline under external acid stress. The conditioner also improved soil moisture retention, showed good biocompatibility, and promoted crop growth. Mechanistic investigations revealed strong synergistic effects among the components: biochar's porosity and montmorillonite's cation-exchange capacity formed a dual adsorption barrier for excess $H^+$, dolomite provided continuous $CO_3^{2-}$/$HCO_3^-$ release for sustained neutralization, and the cross-linked network enabled slow release of buffering agents, thereby suppressing re-acidification[1][2]. Overall, this study presents a high-performance composite conditioner with synergistic amelioration mechanisms, offering an effective and sustainable approach for mitigating soil acidification and enhancing long-term soil health.

**Keywords: Composite soil conditioner; Soil acidification; Acid-buffering capacity; Sustainable agriculture**

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# Effect of straw incorporation on the formation of roots-surface iron plaque in rice and soil cadmium availability

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**ABSTRACT**

The rotation of oilseed rape and rice in southern China typically incorporates alternating periods of flooding and drying during the rice cultivation season. However, this pattern has led to cadmium release during drainage periods, resulting in excessive cadmium levels in rice grains. This is closely linked to the transformation of iron, sulfur and cadmium in the soil, as well as the formation and structural characteristics of the root-surface iron plaque formed by rice. Nevertheless, limited research has examined how rape straw incorporation influences the formation of iron plaque on root surfaces and the availability of cadmium in the rhizosphere, hindering the development of agronomic strategies to regulate cadmium uptake in rice through straw return management. Consequently, this study employed waterlogged soil incubation and rice rhizotron experiments to investigate: the formation of soil $SO_4^{2-}$ and the mechanisms of sulphide reduction and $S^{2-}$ formation driven by sulphate-reducing bacteria during rape straw decomposition; the reduction of $Fe^{3+}$ and formation of $Fe^{2+}$ driven by iron-reducing bacteria in response to soil Eh changes. This clarified how rape straw incorporation affects the concentration and composition of iron plaque on rice roots, as well as how it affects cadmium availability in the rhizosphere. According to our research, the iron plaque's formation changed dynamically during each stage of the growth period. Root iron plaque dissolved as a result of field drying and drainage during the filling stage. Cadmium uptake by roots and its transfer to different above-ground tissues were prevented by the formation of root iron plaque. Rape straw incorporation promoted sulphate migration and accumulation on rice root surfaces, where it was reduced to $S^{2-}$, thereby influencing iron redox processes and consequently affecting iron plaque formation. These processes regulated $Cd^{2+}$ precipitation, dissolution, and migration in soil. Rape straw application decreased soil Eh, which mostly decreased cadmium availability. But as soil DOC decreased throughout the mid-to-late phases of flooded incubation (after 45 days), soil solution Eh increased, thereby raising cadmium availability. Subsequent investigations will further explore the relationship between the release of $Cd^{2+}$ induced by the oxidation of CdS and FeS-Cd coprecipitates in soil and the cadmium sequestration capacity of the iron plaque on rice roots.

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# Mechanisms of organic matter accumulation and pH buffering enhancement in Ultisol under long-term straw-derived amendments

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## ABSTRACT

Straw return is an important agricultural practice for increasing soil organic carbon (SOC) and improving both fertility and acid buffering capacity (pHBC) in Ultisols. Common straw-return strategies include direct straw incorporation, application of straw-derived manure, and use of straw biochar. Nevertheless, the mechanisms through which long-term application of these different straw-derived amendments influences SOC accumulation and pHBC within particulate organic matter (POM) and mineral-associated organic matter (MAOM) remain poorly understood. This study combined microbial biomarkers with $^{13}C$ nuclear magnetic resonance spectroscopy to examine the dynamics of microbial- and plant-derived carbon in POM and MAOM under different straw-derived amendments, along with their impacts on SOC molecular composition. Compared with inorganic fertilizer alone (NPK), equal-carbon inputs of straw (NS), straw plus manure (NSM), and straw biochar (NC) increased SOC by 34.2%, 91.3%, and 158.3%, respectively, and enhanced bulk soil pHBC by 0.8%, 11.4%, and 7.7%. The NSM treatment synergistically increased the accumulation of both microbial- and plant-derived carbon in POM and MAOM, significantly raising protein and lignin contents. The NS treatment mainly enhanced plant-derived carbon and lignin content in POM, whereas the NC treatment largely retained original biochar carbon within POM, increasing its char content. Functionally, the NSM treatment significantly raised the abundance of active functional groups in POM and showed the highest concentrations of –COOH, –OH, and $–NH_2$ groups in MAOM, thereby substantially improving the pHBC of POM, MAOM and bulk soil. The NC treatment increased active functional groups in POM, enhanced its pHBC, and contributed to moderate pHBC improvement in bulk soil. In contrast, the NS treatment did not significantly improve pHBC in either POM or MAOM, limiting its overall effect on bulk soil pHBC. Collectively, these results demonstrate that combined straw and manure application enhances pHBC more effectively by promoting microbial-derived carbon accumulation, which in turn increases protein content and key functional groups involved in acid buffering.

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# Aluminum Toxicity is Key to Regulate Maize Yield in Ultisol under Different Nitrogen Fertilizer Treatments: A Long-Term Field Trial

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## ABSTRACT

Excessive nitrogen fertilizer application is a primary driver of soil acidification. However, long-term observational data on the rates of soil acidification induced by different types of nitrogen fertilizers are scarce. Soil acidification profoundly impacts soil quality, biodiversity, and crop productivity, yet the intricate mechanisms by which it mediates aluminum toxicity, nutrient availability, and microbial community dynamics to affect crop yield remain unclear. This study utilized a 9-year field experiment to investigate the soil acidification rates and their subsequent impact on crop yield under five different nitrogen fertilizer treatments: ammonium sulfate (AS), calcium nitrate (CN), urea (U), controlled-release urea (UR), and urea with straw incorporation (US), all applied in conjunction with superphosphate. Our findings revealed that, with the exception of the CN treatment, all other nitrogen fertilizer treatments exacerbated soil acidification. Ammonium sulfate exhibited the strongest acidification effect, accelerating the process in the 0-40 cm soil layer. Urea-based treatments showed a secondary acidification effect, primarily occurring within the 0-20 cm depth. Severe acidification led to substantial dissolution of active aluminum, significant reductions in calcium, magnesium, and potassium nutrients, and a decline in bacterial and fungal diversity, ultimately resulting in substantial maize yield losses. Mechanistic analysis indicated that severe soil acidification in red soil primarily reduces crop yield by increasing $Al^{3+}$ concentrations, which in turn impairs nitrogen use efficiency. This is attributed to the accumulation of dissolved $Al^{3+}$ on root surfaces in both exchangeable and complexed forms. This not only alters root morphology, significantly reducing total root length, surface area, root diameter, and root tip number, but also its uptake by aboveground plant parts suppresses chlorophyll synthesis and limits maize plant height. In contrast, the contributions of decreased mineral nutrient availability and altered microbial community structure to the inhibition of maize yield were relatively minor. These results provide a foundational basis for optimizing agricultural nitrogen fertilizer application practices and developing sustainable management strategies for acidic soils.

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# Machine learning reveals that duration dominates rate in driving soil nitrogen cycling responses to long-term fertilization

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**ABSTRACT**

Intensive nitrogen fertilization in agricultural ecosystems has profound impacts on soil nitrogen cycling, yet the mechanistic understanding of how long-term nitrogen inputs alter microbial-mediated nitrogen transformations remains limited. While previous research has focused primarily on application rates, the temporal dimension of nitrogen management has been largely overlooked. Here, we present a global meta-analysis of 2,824 observations from 88 field studies specifically examining how nitrogen application duration, rather than just amount, shapes soil nitrogen cycling processes. Machine learning analysis revealed application duration as the dominant driver of nitrogen cycling changes, explaining greater variance than that explained by application rates across all functional genes examined. Long-term nitrogen application (>20 years) dramatically increased ammonia-oxidizing bacteria (AOB) abundance by 904% while modestly affecting ammonia-oxidizing archaea (AOA) by 142%, fundamentally altering the balance of ammonia oxidation processes. In acidic soils with long-term nitrogen application, AOB responses (1,107%) substantially exceeded AOA responses (179%), demonstrating that substrate availability becomes the primary driver of microbial community structure structure under long-term nitrogen enrichment. Our findings demonstrate that nitrogen application duration, more than amount, determines soil nitrogen cycling responses, creating progressive changes with substantial shifts occurring after 20 years of continuous fertilization. These results reveal duration-dependent mechanisms that provide a new framework for nitrogen management, enabling simultaneous maintenance of agricultural productivity and reduction of environmental impacts through duration-optimized application strategies.

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# The amelioration effects of different biomass and their derived biochars on acidified yellow cinnamon soil under equal raw material mass conditions

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**ABSTRACT**

Due to its alkaline properties, biochar has been widely applied in the amelioration of acidic soils. However, most existing studies have evaluated its effectiveness based on equal application rates of biochar mass, with limited comparative research conducted relative to the feedstock. In this study, biochars were produced from corn stover and pig manure at pyrolysis temperatures of 300°C, 500°C, and 700°C. The alkalinity characteristics and contribution ratios of four major components were analyzed. A laboratory incubation experiment was conducted to assess soil improvement under equivalent raw material input. Results indicated that pig manure-derived biochar exhibited higher alkalinity, pH, and contents of nitrogen (N), calcium (Ca), and magnesium (Mg) compared to corn stover-derived biochar, whereas carbon (C), hydrogen (H), and potassium (K) contents were relatively lower. Total alkalinity in both biochars increased with rising pyrolysis temperature. The contribution ratio of organic alkalinities increased, while carbonate and other inorganic alkalinities contents declined when the pyrolysis temperature exceed 500°C. During the incubation period, both pig manure and its corresponding biochar steadily elevated soil pH, with the raw pig manure treatment showing the most pronounced effect. In contrast, the corn stover treatment initially reduced soil pH, and its derived biochar showed no significant impact on pH adjustment. Compared to the control, the pig manure treatment significantly enhanced soil available nitrogen content, with the greatest accumulation observed for nitrate nitrogen, whereas corn stover application decreased soil nitrate nitrogen levels. Real-time quantitative PCR analysis revealed that both pig manure and its biochar substantially increased the abundance of ammonia-oxidizing bacteria and archaea, with the pig manure treatment exhibiting a significantly greater effect than other treatments. In conclusion, under equal raw material mass input, pig manure and its biochar demonstrate superior efficacy in rapidly ameliorating acidic soil compared to corn stover-derived materials. Furthermore, raw pig manure not only exhibits the strongest improvement potential but also contributes significantly to nitrogen enrichment.

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# Differences in life history strategies of bacteria between paddy and upland soils and implications for carbon sequestration

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**ABSTRACT**

Previous studies on the life strategies of soil bacteria in response to organic matter (OM) inputs have largely focused on unsaturated upland soils, rather than flooded soils. Through meta-analysis and soil incubation experiments, we found that, unlike in upland soils, Actinobacteria and Proteobacteria in paddy soils appeared oligotrophic. This divergence was because the same bacterial phylum in paddy and upland soils comprised different members with distinct physiological and ecological characteristics. The life history strategies of some bacterial phyla could shift with soil moisture and the C:N ratio of added OM. Importantly, the content of bacterial necromass carbon in soil mineral-associated organic carbon was related to copiotrophs. Therefore, bacteria that contribute to organic carbon sequestration in upland soils may not play the same role in paddy soils (Fig. 1). These findings can help improve our application of the copiotroph-oligotroph framework and advance our understanding of bacteria-mediated carbon sequestration processes in flooded soils.

Prior to this study, we conducted a preliminary methodological investigation to determine whether added OM and storage influence the characterization of soil microbial communities. The results indicated that both freshly-added and aged plant residue did not affect bacterial communities in air-dried soils. However, for alkaline and oligotrophic air-dried soils, storage might have an effect even at - 80 °C (Yang et al., 2025). This methodological work can help us optimize the storage of soils for microbial analysis and understand microorganism survival in dry soils.

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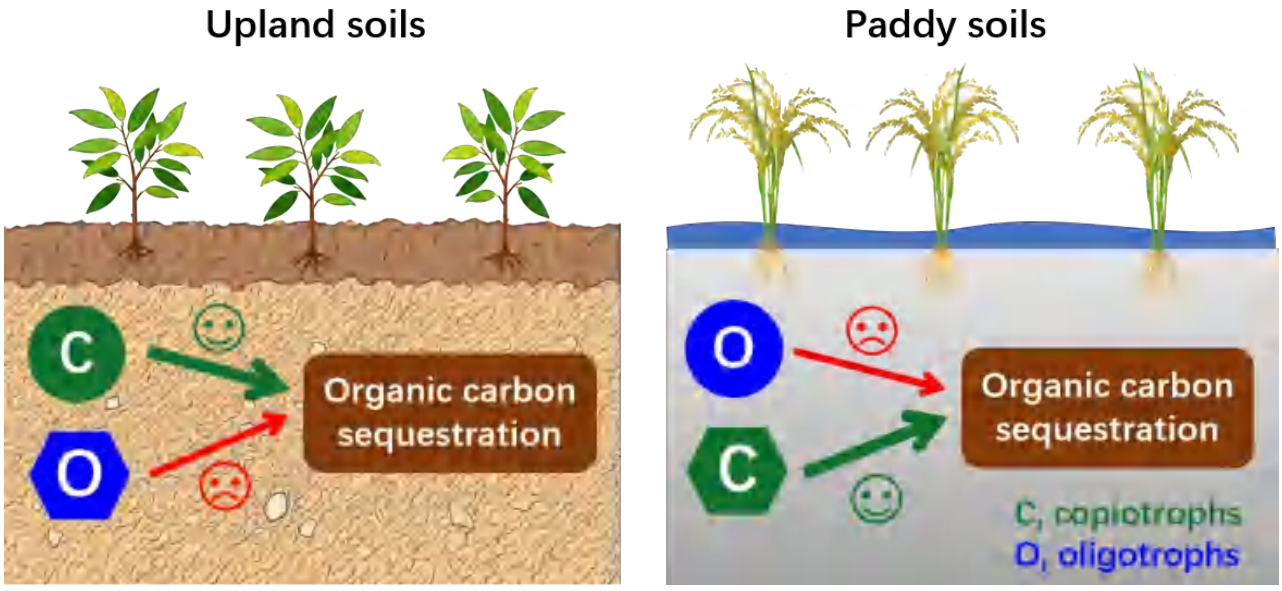



**Fig. 1** Copiotrophs promotes organic carbon sequestration, but copiotrophs in upland soils may be oligotrophs in paddy soils.

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# Cross-regional transfer learning to predict acid sulfate soils in Finland using Random Forest

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**ABSTRACT**

The assessment and proper use of land for various purposes requires digital soil mapping. Nowadays, the use of machine learning techniques in digital soil mapping has been a major breakthrough. The resulting maps are accurate, objective and easily reproducible. Furthermore, the process is less expensive than traditional methods. A supervised machine learning technique needs soil samples and environmental covariates for the creation of a map. In general, the lack of soil samples in some regions is a major issue in digital soil mapping, as this prevents the creation of the maps. In the case of acid sulfate (AS) soils, the absence of maps can be a high risk for the environment. This is due to the fact that AS soils can lead to environmental damage when they are oxidized during the drainage of the land. Therefore, in the unavailability of maps, AS soils may be accidentally drained by external activities related to agriculture, forestry or urban activities. A possible solution for mapping areas with few soil samples is to use soil samples from other regions. In a previous work, we showed that a machine learning model is able to correctly classify soil samples from a region where it had not been trained if the composition of the soils of the region where it has been trained is the same [1]. In this study, we have analyzed whether a machine learning technique is capable of predicting the AS soils of a region when the model has been trained in a region with a very different soil composition. For this, four different regions located in the coastal areas of Finland have been considered. As in the previous work, the machine learning method used is Random Forest, which has shown very high predicted abilities for the classification and prediction of AS soils [1-5]. The results show that in the most of the cases analyzed, the model is able to correctly predict the AS soils when the model is trained with soil samples from other regions. This is a significant advancement in the field because it permits the first recognition of regions with a limited number of soil samples.

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# The Acid Sulfate Soil Distribution Mapping in The Buffer Area of Nusantara Capital City, Kalimantan, Indonesia

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**ABSTRACT**

The new capital city of Nusantara (IKN), Indonesia consist of various landscapes, including the 168 square kilometres mangrove forest along the Balikpapan Bay. The development planning of hub ports on this IKN buffer areas become a concern when proper environmental impact analysis, especially pertaining of the occurrence distribution of acid sulfate soil (ASSoils), has not been well conducted. The exploitation of mangrove pyrite content's soil will expose the pyrite to the air and its oxidation will severely degrade the soil and water quality of surrounding areas. To avoid these failures, the development on the coastal areas urgently needs the information of distribution of ASSoils, vertical and horizontally using robust and comprehensive approaches. This research aims to use remote sensing and hydro-geomorphological approaches to estimate the distribution of ASSoils in the mangrove ecosystem area of the IKN Buffer Zone.

Multi-spectral satellite imageries are processed to derive the information of catchment area, mangrove landcover, river and estuary classification, through multi-spectral classification and transformation (NDVI, NDWI, and Tasselled Cap). The model of multi-level landform mapping is used to combine all parameters to generate the hydro-geomorphic units (HGU) representing the mangrove soil formation process and characteristics. Various secondary data of hydrology and geomorphological parameters were integrated into the model to detail the HGU attributes. The soil sampling was conducted to collect mangrove soil of which to be analysed in laboratory. The result show that most of soils contain pyrite with range 1 to 2% associated with HGU 1, 2 and 4 that own combinations of soil and material of claystone, whereas area with pyrite less than 0,5 % related to HGU 3 and 5, with composition of limestone, silty claystone and marl. The more detail soil properties and mangrove types present the correlation between variables however it is less that is expected (<0,6) due to various environmental factors and soil sample handling issues in term of accessibilities. For conclusion and challenges future research collaboration are mangrove soils are critical to blue carbon strategies in Indonesia, serving as major carbon sinks that must be accurately assessed and protected. Comprehensive soil analysis is essential, especially in mangrove ecosystems where pyrite exposure and acid sulfate formation pose hidden environmental risks. Current soil sampling technologies face limitations in accessibility, especially in remote coastal zones, requiring innovation and logistical support. Standardization of soil handling and laboratory analysis must be aligned with international protocols to ensure data reliability and global comparability.

**Key word :** Acid Sulfate Soils (ASS), Mangrove Hydro-Geomorphology, Remote Sensing Analysis, Pyrite Distribution, IKN Coastal Zone.

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# Coupling of microbial iron and sulfate reduction with organic carbon stabilization in mangrove soil

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**ABSTRACT**

Mangrove soil is a globally important carbon sink. Microbial-mediated iron and sulfate reduction is the major pathway for organic carbon (OC) decomposition in mangrove soil. However, there are also mechanisms that promote the stabilization of OC during the process of microbial iron and sulfate reduction: i) Microorganisms synthesize biomass when decomposing OC; ii) The secondary ferrous minerals generated can protect OC; iii) The $Fe^{2+}$ generated can catalyze the Maillard reaction to transform low-molecular-weight OC to macromolecular OC that is less decomposable. However, the interactions among these mechanisms and their impact on OC stabilization remains unclear. We collected soils from Futian Mangrove Reservation, Shenzhen and did an incubation experiment. There were four treatments: (i) unautoclaved soil + OC; (ii) autoclaved soil + OC; (iii) autoclaved soil + iron-reducing bacteria + OC; (iv) autoclaved soil + sulfate-reducing bacteria + OC. The contributions of microbial anabolism, mineral protection, and $Fe^{2+}$-catalyzed Maillard reaction on OC stabilization were investigated with advanced chemical, spectral, and molecular biology methods. This study can contribute to a better understanding of the coupling between carbon, iron, and sulfur cycles in mangrove soil.

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# Coastal Acid Sulfate Soils and Their Mapping in Finland

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**ABSTRACT**

In Finland, acid sulfate soils (ASS) are sulfur-rich, acid-producing soils typically found below the highest shoreline of the ancient Littorina Sea. This saline phase of the Baltic Sea (9,800–4,000 BP) deposited sediments now found up to 100 meters above sea level due to post-glacial land uplift. At lower elevations, the Littorina Sea sediments are often overlain by deposits formed in a less saline environment during the gradual transition from the Littorina Sea stage to the present Baltic Sea.

Since 2009, the Geological Survey of Finland (GTK) has mapped the occurrence and properties of coastal ASS (cf. Edén et al., 2023), resulting in a public map service and a substantial database on the varying characteristics of ASS. Roughly 10,000 km² of the mapped area is underlain by ASS. The ASS proportion increases from south to north, reaching up to 29% in Lapland, and its highest on agricultural land at 35%. The mapping continues within the MASSIW project, which is partly funded by the Interreg Aurora and the Regional Council of Lapland.

The properties of ASS in Finland are strongly influenced by sedimentological conditions. ASS materials are often fine-grained and organic-rich clays and silts deposited in deep water, now common in low-lying agricultural areas of Southern Finland and Ostrobothnia. Coarser ASS materials occur in river delta and littoral deposits, especially along the coast of Northern Ostrobothnia. The largest coarse-grained ASS deposits are often associated with eskers that were reworked by wave action during the Littorina Sea phase. The acid-producing potential of ASS, determined by Titratable incubation acidity (TIA), correlates with lithology: gyttjas and organic-rich clays and silts have the highest potential, while coarse materials produce less acid but may still pose environmental risks.

In Finland, two main ASS types are recognized: sulfuric soils, which actively produce acidity and release harmful metals, and hypersulfidic soils, which can become active if redox conditions change following hydrological disturbance. Sulfuric soils are most commonly found in agricultural lands where the soil has been drained to 1–2 meters depth. Although forest soils have also been extensively drained in Finland, sulfide-rich layers in forest areas are often covered by peat, and drainage has not typically reached the sulfide-bearing subsoil (hypersulfidic soil).

In the current ASS map, all ASS types of have been combined into a single layer representing the occurrence of ASS. One goal of the MASSIW project is to refine the current ASS map using machine learning and modelling and produce maps that differentiate between various ASS types, lithology, and acid-producing potential.

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# The Effects of Pyrite on Soil Organic Carbon Storage in a Temperate Wetland Coastal Acid Sulfate Soil

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**ABSTRACT**

Coastal wetlands have the potential to store large amounts of soil organic carbon (SOC) as a result of their saturated soils limiting aerobic decomposition. However, these environments also have the potential to form acid sulfate soils (ASS), which are characterised by the formation of Fe sulfides. Despite studies exploring the link between Fe and SOC in terrestrial settings and the potential reservoir of SOC in coastal wetlands, the influence of Fe in ASS on carbon storage in coastal wetlands has yet to be explored. This study aims to investigate the influence of pyrite and subsequent Fe species on the decomposition of SOC in a coastal ASS (CASS). Top soil samples (0-10 cm depth) where taken from the supratidal zone of a coastal wetland at Corner Inlet in Wilsons Promontory, Victoria, Australia dominated by Swamp Paperbark (*Melaleuca ericifolia*). Soils were incubated with additions of organic matter (OM), pyrite and a combination of both under saturated (anoxic) and non-saturated (oxic) conditions, along with replicates using acid-washed sand as the medium. Overall, under anoxic conditions, the addition of pyrite increased $CO_2$ fluxes for sand and soil mediums. However, under oxic conditions, this effect was less pronounced when additional OM was added compared to anoxic conditions. Therefore, the presence of pyrite has the potential to increase $CO_2$ emissions and reduce SOC storage in CASS wetlands.

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# Peat in Australia - Diversity, Values, Risks and the Universal Occurrence of Acid Sulfate Soils in South Australia

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**ABSTRACT**

Australian peatlands span tropical, arid, temperate, alpine and polar settings, yet remain poorly mapped outside Tasmania and the Australian Alps. National reviews highlight gaps not only in peat extent, condition, carbon stocks and hydrological sensitivity, but in paleo-environmental history, fire regimes and peat accrual rates, which have been quantified in very few studies. Within this broader context, South Australia (Sth. Aust.) hosts two major peatland provinces - the Fleurieu Peninsula and Lower South East, the latter comprising spring-fed, groundwater - and surface-water-driven wetlands that, under natural conditions, supported persistent peat accumulation. Additional peatlands also occur in other regions, although these have not yet been assessed for acid sulfate soil (ASS) characteristics.

New evidence from an 82-year paired-site resampling program (Stephens 1942; resampled 2024), combined with recent investigations of Fleurieu swamps, demonstrates that most Sth. Aust. peatland investigated to date contains organic-rich ASS materials, including hypersulfidic, hyposulfidic and sulfuric materials over fine-grained limestone or substrates. Re-examination of archived 1942 cores with contemporary profiles reveals major pedological and biogeochemical shifts where drainage, groundwater decline, drying–rewetting cycles and vegetation change have altered wetland hydrology and peat characteristics.

Undisturbed pre- 1942 sites under native vegetation displayed reversible wetting–drying dynamics, maintaining saturated hypersulfidic organic soils. In contrast, drainage and land- use change drive irreversible formation of sulfuric material, peat oxidation, structural collapse, reduced peat thickness and salt efflorescence. These processes, captured in a predictive ASS soil–landscape model (Fitzpatrick et al. 2025), illustrate how hydrological alteration accelerates pyrite oxidation, mobilises acidity and metals, degrades water quality and threatens peat carbon stability.

Investigations on the Fleurieu Peninsula confirm ASS occurrence in all assessed peatlands sampled, expanding the recognised distribution of inland ASS in cool- temperate regions of Australia. These findings place Sth. Aust. peatlands within the global context of wetland ASS processes and demonstrate their high sensitivity to climatic drying, drainage and vegetation change.

This work provides the first integrated demonstration of the universal occurrence and high vulnerability of ASS across all studied Sth. Aust. peatlands, supporting improved management frameworks and nature- based solutions. The results align strongly with IUSS Working Group objectives and contribute to SDGs related to water quality, agricultural resilience, biodiversity conservation and infrastructure protection.

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# Neutralisation of Acid Sulfate Soils with Industrial Side Streams

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**ABSTRACT**

Sulfide-bearing soils are found along the Finnish coastline. When exposed to oxygen, sulfide minerals oxidise to sulfuric acid, leading to soil acidification and the mobilisation of harmful metals and metalloids into surrounding environments via runoff waters. Such soils are classified as hypersulfidic soils. Once the oxidation process has been initiated, these soils are classified as sulphuric soils, and together with hypersulfidic soils, they form subgroups of acid sulfate soils. Preventing oxidation-induced acidification through neutralisation of hypersulfidic soils is therefore essential to minimise environmental contamination.

This study investigated the neutralisation of acid sulfate soils using industrial side streams as alternative alkaline materials. Three acid sulfate soil materials from the Oulu region in Finland were examined. Two materials were fine-grained silty clays with high sulfur contents (0.8% and 0.7%), while the third was fine sand containing 0.04% sulfur. Chemical analyses were performed to determine the pre-incubation characteristics of both fresh and oxidised samples after 19 weeks of incubation. Total element concentrations were determined by ICP-MS following aqua regia digestion, and leachable element concentrations were analysed using a two-stage shaking test (SFS-EN 12457-3).

Laboratory oxidation experiments were conducted over 19 weeks to evaluate the effectiveness of industrial side streams, including alkaline ashes, slags, and crushed concrete, applied at varying dosages as neutralising agents. Calcite was included as References material. Soil pH was monitored throughout the incubation, and the leaching behaviour of metals and metalloids before and after oxidation was assessed using a modified SFS-EN 12457-2 leaching test.

Based on the laboratory results, the most promising neutralising materials were selected for pilot-scale outdoor testing. Four industrial side streams were applied at two different dosages in box experiments (40 L) and incubated under field-relevant conditions for six months. Soil pH development and element leaching were monitored throughout the test period using the same analytical methods as in the laboratory experiments.

All untreated soils and soils amended with insufficient amounts of neutralising agents acidified to pH < 4 during oxidation, resulting in increased leaching of harmful elements. In contrast, application of 100% of the theoretically calculated neutralisation requirement effectively prevented acidification and significantly reduced the leaching of metals and metalloids in both laboratory and pilot-scale experiments. The results demonstrate that industrial side streams can serve as effective neutralising agents for acid sulfate soils and offer a promising approach for sustainable soil management. However, the practical application of such materials must comply with current fertiliser and environmental legislation.

# Geophysical Methods for Mapping Acid Sulfate Soil Properties

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**ABSTRACT**

Airborne geophysics is effective for identifying large acid sulfate soil (ASS) areas at the catchment scale, but there is a growing need for high-resolution mapping of ASS properties at local scales. The MASSIW-project (funded by the Interreg Aurora and the Regional Council of Lapland) evaluates geophysical methods for characterizing soil properties such as grain size, depth to hypersulfidic material, oxidised horizon thickness, and groundwater depth. The focus is on electromagnetic (EM) methods, particularly GEM-2, and ground penetrating radar (GPR). Both methods have been widely used to map lithology, texture, and stratigraphy, but their application in ASS surveys remains limited.

Fine-grained (<63 µm) and coarse-grained (≥63 µm) Finnish ASS materials show similarly low pH during oxidation, but their impacts differ. Coarse-grained ASS materials have lower buffering capacity, allowing pH to fall below diagnostic thresholds even at low sulfide concentrations. Fine-grained ASS materials, especially with high organic content, has much higher acidifying potential due to higher sulfur concentrations (Mattbäck et al., 2022). These differences influence management: fine-grained soils need stricter monitoring, liming, and drainage control, while coarse-grained soils may allow more flexible approaches.

The study sites represent varying soil characteristics and are all located in Ostrobothnia, western Finland: Söderfjärden (62°59'52.2"N 21°36'19.5"E), a classic ASS site in an ancient meteorite crater with homogeneous, fine-grained, gyttja-containing sediments on farmlands; a sulfuric wetland Sokaluoto (63°35'12.2"N 22°33'28.1"E), with fine-grained, gyttja-containing ASS materials and a distinct boundary between black hypermonosulfidic and grey hypersulfidic layers; a sand mining area Sokaluoto (63°34'57.1"N 22°34'21.0"E), where coarse-grained materials overlie hypersulfidic fine-grained materials; and Viitavesi (63°39'52.2"N 23°24'54.1"E), with large spatial variations in topography and Quaternary sediment distribution.

Soil electrical conductivity (EC) and magnetic properties were measured using GEM-2, while GPR was applied to identify changes in soil composition. Together, these methods provide information on lithology and texture, stratigraphic layering, and the depth to the groundwater table. Preliminary results indicate that GEM-2 effectively detects thick, fine-grained hypersulfidic sediments and differentiates between fine- and coarse-grained soil materials. GPR provides valuable insights into vertical variations in lithology and texture and groundwater depth but is limited to areas with coarser materials.

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# Sulfur Geochemistry of a Sulfuric Wetland in Ostrobothnia, Western Finland

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**ABSTRACT**

The study investigates the geochemical and mineralogical processes controlling the formation, transformation, and stability of metastable iron sulfides, pyrite, and secondary Fe/SO4 minerals in a sulfuric wetland (pH ~3.0). The work aims to improve understanding of acid-generating mechanisms and redox dynamics under highly acidic conditions, with implications for wetland management and risk assessment in acid sulfate soil (ASS) systems. The long-term goal is to identify management strategies that could enable sustainable forestry. This research is part of the MASSIW-project, funded by Interreg Aurora and the Regional Council of Lapland.

In the 1950s, Plottret (63°35'12.2" N 22°33'28.1"E) was a freshwater glo lake located near Karviken. When Karviken was drained in the 1960s, Plottret was presumably partly drained as well, exposing hypersulfidic sediments and leading to the development of a sulfuric wetland. Peat formation, which would have prevented oxidation, was likely inhibited by the sudden drop in the water table. Additional acidification has been promoted by pugging from cattle and wildlife.

A 300 cm deep soil profile was obtained using a D-section peat sampler. The uppermost 10 cm qualifies (>20% organic matter), while the rest of the profile consists mainly of clay with 2–20% organic matter, except for a sandy layer at 120–127 cm (1.1% organic matter) indicating an erosional event. Materials were classified based on field and incubation pH (Boman et al., 2023): sulfuric materials at 0–70 cm; parasulfuric and hypermonosulfidic materials at 70–80 cm (transition zone); hypermonosulfidic materials at 80–120 cm; and hypersulfidic materials from 120–300 cm. The brown-yellow oxidised horizon (to 70 cm) is strongly acidic and contains jarosite and possibly schwertmannite. Sediments between 70–120 cm are black due to metastable iron sulfides, while those between 120–300 cm are grey with black streaks.

Titratable actual acidity (TAA) was measured on oxidised samples (0–70 cm) and titratable incubation acidity (TIA) on reduced samples (70–300 cm), while acid volatile sulfide (AVS) and chromium reducible sulfur (CRS) were analysed on all samples. Both TAA (93–141 mmol H+/kg) and TIA (77–268 mmol H+/kg) were generally high, except in the sandy layer where TIA was much lower. AVS was absent in the oxidised horizon but detected in small amounts (0.02%) just above the transition zone. CRS occurred at low concentrations throughout the oxidised horizon (~0.03%) and increased markedly near the transition zone (0.24%), matching AVS levels. Overall, AVS dominated in black sediment, whereas CRS was dominant in grey sediment.

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# Improved sampling and laboratory methods using chip-trays for assessment and classification of acid sulfate soils

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**ABSTRACT**

The chip-tray method has been extensively used and refined in a wide range of acid sulfate soil (ASS) investigations globally (Fitzpatrick et al. 2010, 2025; Nystrand et al. 2025). The advantages of using chip-trays include rapid field collection and storage of moist soil samples, which offer standardised pH incubation conditions that represents a "realistic tool" to characterise and classify ASS (Isbell & NCST 2021) based on allowing the soil to "speak for itself" (Dent 1986). Field protocol involves using one chip-tray to display the morphology of intact soil samples for visual References and photographed for inclusion in profile descriptions. A second chip-tray is used for incubation pH testing by filling compartments to a thickness of 10mm with samples that are kept moistened with deionized water to prevent excessive desiccation (Fitzpatrick et al. 2010). However, incubation of organic-rich soils on Norfolk Island to identify hypersulfidic material using 10mm thick layers did not create optimal sulfide oxidation conditions unless samples were stirred 4 times per week (Fitzpatrick et al. 2025). Accordingly, Nystrand et al. (2025) recommended using 2 mm thick samples in chip trays for organic-rich and clayey soils in Finland. The laboratory Slab Incubation method also uses 2 mm thick slabs to speed-up incubation processes (Sullivan et al. 2018; Isbell & NCST 2021). This method involves smearing 2 mm slabs of soil with a roller onto a fine gauze mesh (2.0×1.5 mm) strip between 2 mm high spacers. A coarse plastic mesh (10 x10mm) is used to suspend the gauze mesh with smeared sample to allow maximum air penetration to both sides of the slab. Based on the Slab Incubation method, we have made 3 sequential inserts for each chip-tray compartment: (i) two 5mm thick plastic cross tile spaces (20 x 20mm), (ii) strip (4.7 mm X 2.4mm) of stiff plastic mesh (3 mm thick) placed on the 2 tile spaces and (iii) fine gauze mesh (2.0×1.5 mm) strip (4.7 mm X 2.4mm) placed on the stiff plastic mesh. Two compartments are each filled with layers of 2 mm thickness to duplicate samples. Incubation times are substantially reduced (up to 60% compared to 10mm thick layers) in all soils tested because of increased air penetration.

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# Iron oxyhydroxides, oxyhydroxysulfates and efflorescent sulfate salts as indicators of biogeochemical processes at low pH in acid sulfate weathering environments

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**ABSTRACT**

Acid sulfate soils (ASS) with sulfide minerals (i.e., contain hypersulfidic materials) are widely distributed in both coastal and inland regions globally, and if exposed to air, the oxidation of sulfide minerals results in the production of sulfuric acid with the formation of sulfuric materials (pH<4) along with a wide range of profound mineralogical changes. We report on the occurrence, genesis and properties of the wide range of Fe-oxyhydroxides (lepidocrocite), Fe- and Al-oxyhydroxysulfate minerals (schwertmannite, jarosite, natrojarosite, ammoniojarosite, hydronium jarosite) and efflorescent sulfate salts (tamarugite, sideronatrite, gypsum, epsomite, hexahydrite and others) on the surfaces of peats, clay peds and sands from a variety of disturbed wetlands with sulfuric soils from Australia and Finland. X-ray diffraction has been used to determine their mineralogy, inductively coupled plasma mass spectrometry for geochemical characterisation, and acid-base accounting to assess ASS potential. The composition of these minerals is influenced by the biogeochemical conditions of formation in receiving environments.

Salt efflorescence samples from Sulfuric soils with pH values as low as 2.2 in the Coonjimba Billabong, Northern Territory in Australia were found to contain a recently identified mineral giacovazzoite ($K_5Fe^{3+}{}_3O(SO_4)_6 \cdot 10H_2O$), in association with Na-jarosite, tamarugite, and hexahydrite.

As a result of the prolonged drying of freshwater wetlands across Norfolk Island sulfuric organic soils formed with the following prominent precipitates: (i) schwertmannite in ponded water and coating vegetation, (ii) iridescent floating films of schwertmannite on water that produce silver and gold Newton colours, due to “thin-film interference, (iii) lepidocrocite and schwertmannite on soil surfaces and (iv) ammoniojarosite coating vegetation on sulfuric organic soils through sorption or coprecipitation of ammonia concentration from cattle dung deposition.

In drying wetlands at Plottret near Socklot, in western Finland Sulfuric organic soils formed with prominent yellow precipitates of hydronium jarosite with traces of ammoniojarosite on micro-mounds and thin yellowish-brown precipitates of schwertmannite in adjacent hollows through likely sorption or coprecipitation of ammonia concentration from Moose dung deposition.

In drying wetlands and Lake Alexandrina during Australia's Millennium drought Sulfuric sandy soils with pH <2 formed with dominant sideronatrite [$Na_2Fe(SO_4)_2.OH.3H_2O$] and minor tamarugite. During subsequent rain events yellowish-red precipitates of schwertmannite formed in patches adjacent to where the sideronatrite formed due to the rapid transformation of sideronatrite to schwertmannite in rainwater.

These Fe-oxyhydroxides, oxyhydroxysulfates and efflorescent sulfate salts can be used as powerful indicators of the prevailing environmental conditions and highlight the potential for severe water quality degradation and risks to aquatic biota.

# Why the Effects of Vegetation Restoration on Soil Properties May Be Overestimated: Evidence from 30 Years of Long-Term Monitoring on the Loess Plateau, China

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**ABSTRACT**

Vegetation restoration is widely regarded as an important strategy for erosion control, soil recovery, and ecosystem improvement. However, the effects of vegetation restoration on changes in soil properties may be overestimated when the combined influences of topography, parent material, and other soil-forming factors are overlooked. Based on 30 years of continuous in situ monitoring at the Jixian National Forest Ecosystem Observation and Research Station in the loess region of western Shanxi, China, this study evaluated the effects of vegetation restoration on soil physicochemical properties, ecological stoichiometry, microbial processes, and soil organic carbon stability, and interpreted these effects within a soil-forming-factor framework.

(1) Soil physical properties were more strongly influenced by topography than by vegetation restoration alone. Slope and slope aspect explained variations in bulk density, total porosity, and capillary porosity more effectively. (2) The effects of long-term vegetation restoration on soil nutrients appeared limited and asynchronous. Although soil organic carbon (SOC) and total nitrogen (TN) increased slightly, total phosphorus (TP) declined, suggesting that nutrient changes cannot be interpreted as a consistent improvement driven by vegetation restoration. (3) Microbial communities were sensitive to vegetation restoration, but their responses more likely reflected functional reorganization driven by changes in substrate inputs, water availability, and nutrient limitation. (4) In the subsoil, variations in SOC stability were controlled by hillslope transport and transformation processes. Attributing SOC patterns solely to vegetation type may overestimate the vegetation restoration effect.

Overall, vegetation, however, represents only one component of the biological factor in soil formation. Soil properties are shaped jointly by climate, topography, parent material, time, and human activities. In the loess residual tableland and gully region, complex terrain, water redistribution, erosion and deposition processes, and thick loess parent material can mediate soil variation. Therefore, attributing post restoration soil differences entirely to vegetation restoration may overstate the true role of vegetation itself.

**Keywords:** vegetation restoration; soil-forming factors; soil properties; ecological stoichiometry; soil organic carbon; Loess Plateau; long-term monitoring.

# The regulation of microbial life-history strategies on soil carbon cycling

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**ABSTRACT**

Life history strategies of soil microbiomes determine their environmental adaptability and improve mechanistic understanding of soil carbon-climate feedback. Here, we investigated trade-offs among microbial high yield (Y), resource acquisition (A), and stress tolerance (S) strategies and their consequences for soil carbon mineralization potential along an aridity gradient spanning 9.6 million square kilometers. Results indicate increases in microbial carbon allocation toward resource acquisition and stress tolerance come at the expense of growth efficiency. The responses of Y-A-S strategies to increases in aridity follow a series of sequential thresholds. Aridification-induced abrupt increases in A- and S-strategies cause a sudden decrease in Y-strategy. Importantly, our findings link microbial Y-A-S life history strategies to SOC mineralization potential. We suggest that once aridity exceeds all thresholds of the Y-A-S strategies, the SOC mineralization potential shows a sharp increase, highlighting the cascading effects of aridity-induced shifts in microbial life history strategies on soil carbon cycling at a biogeographical scale. Overall, our findings suggest that variations in microbial Y-A-S strategies significantly influence soil carbon cycling and can be incorporated into microbial models.

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# Heatwaves Increase Greenhouse Gas Emissions from Different Ecosystems

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**ABSTRACT**

Climate change has increased the frequency, intensity, and duration of extreme climate events worldwide. Those extreme climate events are either made more likely or more severe by human-driven greenhouse gas emissions. Extreme events disrupt the soil–plant–atmosphere continuum, destabilizing water and energy balances and altering the carbon cycle in terrestrial ecosystems. One of those extreme climate events is heatwaves. Our laboratory-based experiment indicates that heatwaves increase both $CO_2$ and $N_2O$ emissions without affecting $CH_4$ emissions in both agricultural and forest soils. Those responses increase with increasing frequency of heatwave events. Our field-based experiment, incorporating simulated grazing intensity and heatwave frequency treatments, indicates that heatwave events increase soil $CO_2$ but not $N_2O$ emissions in a rangeland ecosystem, regardless of simulated grazing intensity. Grazing intensity and heatwave treatments interacted to affect $CH_4$ emissions, with heatwave increasing $CH_4$ oxidation under heavy grazing. Our studies suggest a positive feedback mechanism of heatwaves to climate change. Heatwaves may also reduce plant photosynthesis rates and shift the allocation of photosynthates among plant components. Such shifts in biomass carbon allocation may further amplify the adverse effect of extreme climate events on ecosystem productivity. Long-term field experiments that incorporate multiple climate change factors need to be conducted at large scales to examine their effects and feedback mechanisms within the soil-plant-atmosphere continuum, thereby allowing us to better understand the impact of extreme climate events on terrestrial ecosystems.

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# Coupling and decoupling of soil carbon, nitrogen, phosphorus and potassium stocks along a 6000 km northeast-southwest temperature gradient in China

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## ABSTRACT

Soil nutrient stocks are crucial to ecosystem stability. Previous studies have examined variations in soil carbon (C), nitrogen (N), and phosphorus (P) stocks in response to climate warming; however, there is a lack of knowledge regarding how climate warming affects soil potassium (K) stock, although K is the second most abundant nutrient in plants. Furthermore, how climate warming affects the balance of C, N, P, and K stocks in the soil remains to be elucidated. Here, we investigated the changes in soil C, N, P, and K stocks under climate warming by sampling soil along a 6000 km northeast-southwest temperature gradient in China. We found that soil C and N stocks significantly decreased with increasing temperature. Soil C and N stocks exhibited a stronger response to temperature than to soil properties (i.e., soil pH, soil clay, silt, and sand contents), vegetation and soil types. However, soil P and K stocks remained stable with increasing temperature. Variations in soil P and K stocks were primarily regulated by soil properties, vegetation type, soil type, and soil parent material type. Frigid temperate coniferous forest, temperate coniferous and broad-leaved mixed forests and alpine meadow possessed the highest soil C and N stocks, followed by subalpine grassland, alpine grassland, temperate typical steppe and temperate meadow steppe. In contrast, semi-desert grassland held the lowest soil C and N stocks. Soil P and K stocks in subalpine grassland were higher than those in the other vegetation types. However, semi-desert grassland retained the lowest soil P and K stocks. Umbrisols and Luvisols held the largest soil C and N stocks, followed by Cambisols, Leptosols and Chernozems. Calcisols had the lowest soil C and N stocks. For soil P and K stocks, their contents in Leptosols were higher than those in the other soil types. Furthermore, soil C stock was closely correlated with soil N stock across this temperature transect, suggesting that coupled links between soil C and N stocks persisted across this temperature transect. The ratio of soil C or N stocks to soil P or K stocks decreased with increasing temperature, indicating that soil C and N stocks declined more rapidly than soil P and K stocks under climate warming, thus resulting in the decoupling of C-N and P-K stocks in soil. Our findings revealed that soil might become more limited in C and N than in P and K because of climate warming.

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# Forest methane sink under climate change

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**ABSTRACT**

In 2020, anthropogenic methane ($CH_4$) emissions decreased due to COVID-19 containment policies, but there was a substantial increase in the concentration of atmospheric $CH_4$. Previous research suggested that this abnormal increase was linked to higher wetland $CH_4$ emissions and a decrease in the atmospheric $CH_4$ sink. However, the impact of changes in the soil $CH_4$ sink remained unknown. To address this, we utilized a process-based model to quantify alterations in the soil $CH_4$ sink of terrestrial ecosystems between 2019 and 2020. By implementing the model with various datasets, we consistently observed an increase in the global soil $CH_4$ sink, reaching up to 0.35 ± 0.06 Tg in 2020 compared to 2019. This increase was primarily attributed to warmer soil temperatures in northern high latitudes. Our results emphasize the importance of considering the $CH_4$ sink in terrestrial ecosystems, as neglecting this component can lead to an underestimation of both emission increases and reductions in atmospheric $CH_4$ sink capacity. Furthermore, these findings highlight the potential role of increased soil warmth in terrestrial ecosystems in slowing the growth of $CH_4$ concentrations in the atmosphere.

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# Root exudate-mediated microbial gene activation drives phosphorus mobilization in mixed Chinese Fir species plantations

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## ABSTRACT

The escalating consumption patterns associated with industrialization and economic development have led to deforestation, biodiversity loss, increased greenhouse gas emissions, and widespread pollution. Modern agriculture and forestry face a range of significant challenges, with the depletion of soil phosphorus resources representing a critical and increasingly pressing concern. In this study, we conducted a 15-year transformation experiment in subtropical China and found that interplanting *Schima superba* with Chinese fir significantly increased rhizosphere P availability. Sequential P fractionation revealed a notable shift from stable P forms to moderately labile and labile P pools in mixed plantations, with $NaHCO_3$-Po increasing by 108% and NaOH-Po by 58.3% compared to pure plantations. Metabolomic analysis identified four organic acids, oxoproline, alanine-2, aconitic acid, and *N*-carbamylgluta mate-4 (*NCG* 4), secreted exclusively by Chinese fir roots in the mixed-species system. These root exudates were strongly correlated with $NaHCO_3$-Po levels and activated a microbial P-solubilization gene network. This included upregulation of inorganic P-solubilizing genes (*ppk*, *ppx*, and *pqqD*), high-affinity phosphate transporters (*pstA*, *pstB*, and *pstC*), and P-starvation response regulators (*phoB*, *phoP*, and *phoU*). Partial least squares path explaining 99%, 91%, and 81% of the variations in labile, moderately labile, and stable phosphorus fractions and modeling further indicated that changes in rhizosphere P fractions were driven by the interactions among root exudates, microbial functional genes, and environmental factors (Fig. 1). Together, these findings support a synergistic "root exudate-microbial gene" mechanism that transforms stable P forms into plant-available P, offering a blueprint for designing rhizosphere-engineered mixed-species plantations to overcome P limitation and promote sustainable forestry (Fig. 2).

**Keywords:** Chinese fir, Root exudates, Mixed-species plantations, Phosphorus availability, Metagenome



Fig. 1. PLS-PM illustrating how planting pattern, root exudates, and phosphorus gene abundance influence P concentration in the rhizosphere soil of Chinese fir under different planting patterns.

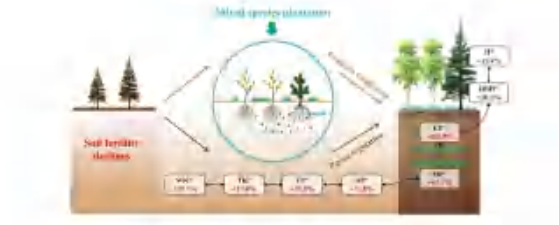


Fig. 2. Root exudates and phosphorus cycling genes jointly mediate phosphorus transformation in the rhizosphere soil. SOC, soil organic carbon; TP, total phosphorus; AP, available phosphorus; TK, total potassium; LP, The labile P; MP, The moderately labile P; DBH, diameter at breast height; H, height.

# Phosphorus in (semi-)natural soils: concentration, stock, dynamics, and drivers

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**ABSTRACT**

Phosphorus (P) is a major nutrients for all organisms. Phosphorus in terrestrial organisms is mainly derived from soils, therefore soil P affects the growth and development of plants, soil microbes and other organisms, and thus key ecosystem functions and processes such as plant production, soil respiration and ecosystem carbon storage. Despite the knowledge gained and numerous site-level explorations or examinations, our understanding of soil P dynamics remain incomplete, in particular at the global scale. This has hindered our understanding of the role of P under global change, and its incorporation into land surface models. In the last decade, we have studied the concentrations, stock, dynamics, and drivers of P in (semi-)natural soils, at local, regional, and global scales. We have generated global datasets and maps of P in total and available forms, and P fractions separated by the Hedley fractionation procedure, and identified climate and parent materials as the key drivers of global variations in soil P concentrations. The improved understanding and datasets have been contributing to the representation and benchmark of soil P dynamics in land surface models.

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# Effects of nitrogen deposition on plant community structure and niche characteristics in typical steppe

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## ABSTRACT

Atmospheric nitrogen deposition, as an environmental problem facing the world, has a variety of effects on grassland ecosystems. In order to analyze the corresponding mechanism of typical steppe plant communities on global change-nitrogen deposition, a simulated nitrogen deposition experiment was designed in the typical steppe of Ewenki Banner, Inner Mongolia in 2017.Nine nitrogen treatments were set up, and the pure nitrogen amounts were 0,25,50,75,100,125,150,175,200 kg · $hm^{-2}$ · $a^{-1}$, respectively, expressed as CK, N25, N50, N75, N100, N125, N150, N175, N200. The effects of nitrogen addition on plant community structure and niche in typical steppe in different years ( 2021-2023 ) were studied. The results showed that the number of species showed high nitrogen application level ( N200 ) < low nitrogen application level ( N15-N50 ). From 2021 to 2023, with the increase of nitrogen application level, the aboveground biomass ( AGB ) showed a significant increasing trend ( $P < 0.05$ ). From 2021 to 2023, the addition of low nitrogen level significantly increased the Shannon-Wiener index and Margalef index of plant communities ( $P < 0.05$ ), and the addition of high nitrogen level significantly increased the Simpson index ( $P < 0.05$ ). The soil pH value decreased with the increase of nitrogen application level in different years, and the soil pH value was significantly negatively correlated with the total AGB ( $P < 0.05$ ). Niche breadth is a comprehensive index reflecting the ability of species to utilize various resources. From 2021 to 2023, the niche breadth of L.chinensis was at a high level under nitrogen addition. The niche overlap values of species were mainly concentrated in the range of 0.3-0.8, and the average niche overlap increased first and then decreased with the increase of nitrogen application level, and the value was the largest under N50 treatment. In general, long-term nitrogen addition increased the productivity of typical steppe plant communities. Among them, the addition of low nitrogen level was positively correlated with the number of community species, Shannon-Wiener index, Margalef index and niche overlap value. The addition of medium and high nitrogen application levels was positively correlated with Simpson index. The key factors affecting the AGB of plant communities under different annual nitrogen additions were soil pH and precipitation. The addition of low nitrogen application level aggravated the competition for resources among plant community species. Under the addition of medium and high nitrogen application levels, the niche overlap value of L.chinensis was low, and low overlap may enable it to differentiate in resource utilization and reduce competitive pressure.

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# Grazing Modulates the Allelopathic Impact of an Invasive Shrub on Soil Seed Bank Diversity and Function: Implications for Grassland Soil Health

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## ABSTRACT

Soil seed banks (SSB) are a vital reservoir of biodiversity and a key component of soil ecosystem services, underpinning plant community regeneration and soil health. While the individual effects of grazing and *Caragana korshinskii* invasion on SSB are known, their interactive effects remain unexplored. This study investigates how grazing management interacts with the allelopathic potential of this invasive woody plant to influence SSB properties, a critical aspect of soil ecological function in the context of global woody plant encroachment. We conducted a controlled experiment in a typical steppe ecosystem. The effects of simulated grazing and aqueous litter extracts from different parts (aboveground, belowground, whole plant) of *C. korshinskii* at varying concentrations on the SSB were assessed via a seedling emergence assay. The aqueous litter extracts of *C. korshinskii* significantly suppressed key SSB indicators of soil ecological function, including seedling emergence density, species richness, and seedling biomass ($P < 0.05$). The inhibitory effects followed the order: belowground parts (BP) > whole parts (WP) > aboveground parts (AP). BP extracts caused reductions of 28.9%, 36.6%, 29.0%, and 31.1% in emergence density, species richness, aboveground, and belowground seedling biomass, respectively. These allelopathic effects were concentration-dependent. Crucially, the experimental grazing treatment significantly alleviated this suppression. Under grazing conditions, the presence of extracts resulted in increases of 52.6%, 23.7%, and 46.3% in seedling emergence density, species richness, and belowground biomass, respectively, compared to non-grazed conditions. Our findings demonstrate that invasive woody plants can exert strong allelopathic pressure on the soil's regenerative capacity, potentially compromising soil biodiversity and ecosystem function. However, appropriate grazing management can modulate this negative impact, helping to maintain the ecological integrity of the soil seed bank. This study highlights that soil ecological processes, such as seed bank dynamics, are critical for ecosystem resilience. The results provide a scientific basis for managing soil ecosystem services and promoting grassland soil health under scenarios of plant invasion and land use change.

**Keywords:** Allelopathy; Grazing management; Soil seed bank; Soil health; Ecosystem services

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# Study on the Influencing Mechanisms of Mercury Accumulation Characteristics in Grassland Soils of Guizhou Province Under the Context of Ecological Restoration

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**ABSTRACT**

Grassland ecosystems cover approximately 40% of the global terrestrial area. As core mercury sinks and carbon pools in terrestrial ecosystems, their mercury and carbon cycling processes exert a pivotal regulatory role in global biogeochemical cycles and environmental health. In the core karst region of Guizhou Province, ecological restoration initiatives have effectively facilitated grassland rehabilitation. However, the response of mercury migration and accumulation in grassland soils to grassland restoration under varying geomorphological conditions remains poorly understood, which constrains the assessment of soil environmental health in the fragile areas of Southwest China.

In this study, 127 grassland soil profiles were collected across diverse geomorphological systems throughout Guizhou Province, and a total of 1312 soil samples were obtained by sectioning the profiles at different depths. Five indicators were analyzed for each sample, including total mercury concentration (THg), dissolved mercury concentration (DHg), pH value, soil organic carbon (SOC), and dissolved organic carbon (DOC). Additionally, data on the Normalized Difference Vegetation Index (NDVI), climatic factors, soil slope, and land use type changes since 1990 were integrated to decipher the mercury-carbon coupling mechanism and identify the underlying environmental driving factors. Preliminary statistical results indicate that the average THg concentration in grassland soils of karst areas is 150.5±77.7 ug/kg, with a corresponding average SOC concentration of 0.74±0.59 %. In contrast, non-karst areas exhibit a higher average THg concentration of 247.2±108.5 ug/kg and a significantly higher average SOC concentration of 2.79±2.10 %. This study aims to clarify the accumulation characteristics and stability changes of mercury in Guizhou's grassland soils under the context of ecological restoration, and to reveal the regulatory role of karst landforms in mercury migration and transformation. The findings of this research will provide a robust scientific basis for understanding the mercury-carbon coupling cycle mechanism in grassland ecosystems of the Southwest China karst region, offer valuable data support for soil mercury pollution prevention and control as well as the environmental effect assessment of ecological restoration projects under global change, and hold significant practical implications for enhancing the soil environmental health in fragile ecological zones.

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# Characteristics of Serpentinite Soils in Northern Hokkaido

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**ABSTRACT**

Serpentinite-derived soils are characterized by high concentrations of heavy metals and base cations, which can restrict plant growth [1]. In contrast, wet iron podzolic soils with high organic carbon content in the surface layers have been reported in northern Hokkaido, the northernmost prefecture of Japan, despite the presence of serpentinite geology [2]. This suggests that serpentine soils in northern Hokkaido differ from typical serpentinite-derived soils found in Honshu, the main island of Japan. However, their physicochemical characteristics remain unclear. Therefore, this study aims to clarify the characteristics of serpentinite soils in northern Hokkaido by comparison them with soils derived from sedimentary rock. Soil profile surveys were conducted at two adjacent sites within the Nakagawa Research Forest of Hokkaido University in northern Hokkaido, where serpentinite and sedimentary rock served as parent materials. Soil samples were collected from each horizon. General physicochemical properties of the collected soils were measured, and soil classification was carried out according to the Soil Classification System of Japan [3]. The soil profile surveys revealed that both the sedimentary rock soils and serpentinite soils had A horizons exceeding 10 cm in thickness, indicating that a thick A horizon was developed even in the serpentinite soils. In addition, the organic carbon content of the A horizons was higher in the serpentinite soils than in those on Honshu. Regarding podzolization processes, which are characteristic of podzolic soils, acid oxalate-extractable iron showed its maximum value in the Bs horizon, indicating iron accumulation. However, the chemical analytical values did not meet the criteria for podzolic accumulation horizons defined by the Soil Classification System of Japan, and iron mottling caused by stagnant water conditions was observed. Consequently, the serpentinite soils were classified into the hydromorphic soil group. These results indicate that, in serpentinite soils of northern Hokkaido, soil formation processes are influenced not only by leaching driven by organic acids but also by the aluminum and iron behavior under stagnant water conditions. In addition, this study examines inorganic materials involved in soil organic matter accumulation using density and particle-size fractionation methods to elucidate mechanisms of organic matter stabilization.

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# Influence of Forest Stand Age on Soil Water Dynamics in Semi-Arid Forests of the Loess Plateau

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**ABSTRACT**

Large-scale afforestation is widely applied to control soil erosion and improve ecosystems in semi-arid regions, but it can also increase pressure on limited soil water resources. This study investigated how forest stand age influences soil moisture dynamics, soil water storage (SWS), actual evapotranspiration (ETa), and root water uptake (RWU) in black locust plantations on the Loess Plateau of China. Field observations from 2014 to 2021 were combined with HYDRUS-1D model simulations to compare young (14-year-old) and old (28-year-old) black locust forest stands under wet, normal, and dry climatic conditions. The HYDRUS-1D model showed strong performance in simulating soil moisture, with coefficients of determination ($R^2$) ranging from 0.81 to 0.88 during calibration and from 0.83 to 0.85 during validation, while RMSE values ranged from 0.018 to 0.024. The results showed that total SWS in the 0–300 cm soil profile was consistently lower in the old stand than in the young stand, with reductions of approximately 25–40% across years. In deep soil layers (100–300 cm), SWS in the old stand was 35–60% lower, indicating persistent deep soil water depletion. Actual evapotranspiration was 5–12% higher in the old stand, particularly during dry and normal years. Soil desiccation intensified with increasing soil depth and stand age, with strong desiccation frequently occurring below 100 cm in old stands during dry years. Root water uptake patterns differed between stands, with young stands extracting 25–60% more water from deep soil layers during drought, while old stands relied more on shallow and middle layers. Overall, the results demonstrate that older plantations impose greater stress on deep soil water resources, while younger stands show higher resistance to drought-induced soil desiccation. These findings highlight the importance of considering forest age and climate variability for sustainable afforestation and water management in semi-arid regions.

**Keyword:** Afforestation; forest stand age; soil water storage; root water uptake; HYDRUS-1D.

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# Southern urban forest converted from orchard abandonment: a potentially important $N_2O$ source driven by warm-humid climate

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**ABSTRACT**

In southeastern (SE) China, rapid urban expansion has increased the extent of secondary and plantation forests converted from abandoned orchards, which could be potential hotspots of nitrous oxide ($N_2O$) emissions due to experiencing historical nitrogen (N) fertilizer applications and high N deposition. However, mechanisms underlying the dynamics of soil $N_2O$ emission from these lands remain poorly investigated, particularly under the significant influences of the SE Asian monsoon climate. In this work, we conducted a year-long observation and a short-term manipulation experiment to explore the factors driving soil $N_2O$ emissions from an urban forest converted from abandoned orchards in a mega city of SE China. Our results highlight its critical role as a significant yet underappreciated source of $N_2O$. Elevated concentrations of soil nitrate in the study area were driven by the combined effects of historical fertilization legacies and ongoing N deposition, providing abundant substrates for $N_2O$ emissions. Seasonal rainfall and rewetting events following droughts substantially influenced N dynamics, triggering $N_2O$ flux peaks during periods of rapid soil moisture changes. The annual $N_2O$ emissions in the study area reached 1.02 kg N $ha^{-1}$ $yr^{-1}$, significantly exceeding the emission strengths typically observed in other subtropical forests. The short-term drivers, such as rainfall-induced changes in soil moisture, were found to be critical for pulse releases of $N_2O$, whereas temperature and pH of soil water regulated the seasonal variations of $N_2O$ fluxes. These findings underscore the importance of integrated monitoring to capture both the immediate impacts of extreme climatic events and the long-term trends in emissions. Under sustained N deposition, urban forest soils play a vital role in regional N cycling, emphasizing their significance in global greenhouse gas assessments and strategies for mitigating climate change.

# Tree functional diversity enhances forest carbon and nitrogen storage across gradients

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**ABSTRACT**

Increasing soil carbon and nitrogen storage can help mitigate climate change and sustain soil fertility. Although many biodiversity experiments indicate that higher plant diversity increases soil carbon and nitrogen stocks, whether these effects generalize to natural forests remains debated and how they vary with environmental context is unclear. Using Canada's National Forest Inventory and structural equation modelling, we quantify how tree diversity relates to decadal accrual of carbon and nitrogen in tree biomass and in organic and mineral soil horizons across broad gradients in light, water, and nutrient availability. Greater tree diversity increased soil carbon and nitrogen storage, consistent with experimental expectations. In the organic horizon, raising species evenness from its minimum to maximum increased soil carbon by 30% and soil nitrogen by 42%. In the mineral horizon, higher functional diversity increased soil carbon by 32% and soil nitrogen by 50%. Functional diversity also increased carbon gains in tree biomass, with stronger effects where light and soil nutrients were more available. Across soils, diversity effects intensified at sites with greater water and nutrient availability. Conserving and promoting functionally diverse, even forests, particularly in resource-rich environments, could substantially enhance carbon and nitrogen sequestration in natural forests.

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# Biochar mitigates the effects of nitrogen deposition on soil greenhouse gas emissions via microbial regulation in a subtropical forest

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## ABSTRACT

Subtropical forests play a vital role in global carbon cycling, acting as significant sinks for atmospheric $CO_2$ and $CH_4$. However, intensifying atmospheric nitrogen (N) deposition threatens to disrupt this balance by stimulating soil heterotrophic respiration ($R_H$) and nitrous oxide ($N_2O$) emissions while suppressing $CH_4$ uptake. Biochar amendment is a promising strategy to sequester C and improve soil health, yet its efficacy in counteracting the specific biogeochemical feedbacks triggered by N deposition remains unclear. This study synthesizes findings from a three-year field experiment to elucidate the microbial mechanisms by which biochar modulates soil greenhouse gas (GHG) fluxes under N deposition conditions.

Results showed that the N deposition significantly disrupted soil GHG balances. It stimulated $R_H$ by 8.1–9.8% annually by alleviating nutrient limitations, which upregulated the abundance of the fungal cellulolytic gene *cbh*I and enhanced cellobiohydrolase activity. Similarly, N deposition triggered a surge in $N_2O$ emissions (14.6–25.1%) by fueling nitrification and denitrification, evidenced by increased abundances of AOA*amoA*, *nirK* and *nirS* genes. Furthermore, it suppressed soil $CH_4$ uptake by 17–23%, primarily by inhibiting methanotrophs (*pmoA*) and stimulating methanogens (*mcrA*) via elevated inorganic N. Crucially, biochar amendment effectively counteracted these N deposition-induced negative feedbacks. (1) For $CO_2$: In the biochar application and N deposition treatment, biochar reduced $R_H$ by 8.1–8.9% compared to N deposition treatment alone. SEM analysis revealed this was driven by the suppression of *cbh*I-mediated organic matter decomposition and the promotion of *cbbL*-mediated autotrophic C fixation. (2) For $N_2O$: Biochar reduced emissions by 14.2–22.0% under N deposition. Mechanistically, biochar reduced labile substrates ($NH_4$, WSON) and downregulated the abundance of AOA*amoA*, *nirK* and *nirS*, thereby inhibiting the enzymatic pathways of nitrification and denitrification. (3) For $CH_4$: Biochar reversed the N-induced suppression, enhancing $CH_4$ uptake by 26–42% relative to N alone. This was attributed to increased soil aeration and labile C, which upregulated methanotrophic *pmoA* abundance and oxidation rates, while reduced inorganic N suppressed methanogenic *mcrA* abundance.

Biochar acts as a systemic regulator of soil microbial function, mitigating the global warming potential of N-saturated forests. We estimate that applying biochar to Moso bamboo forests across China could approximately reduce $R_H$-derived $CO_2$ by $7.6\times10^6$ t $yr^{-1}$, decrease $N_2O$ emissions by 1,949 t $yr^{-1}$, and increase $CH_4$ uptake by 6,478 t $yr^{-1}$. These findings underscore biochar's potential as a climate-smart forestry strategy.

# Soil-plant silicon cycle and climate change

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**ABSTRACT**

Silicon is the second most abundant element in soil and widely participates in geochemical cycles. Research on silicon (Si) biogeochemistry and its beneficial effects for plants has received significant attention over several decades, but the reasons for the emergence of high-Si plants remain unclear (Pang et al., 2024). Hypotheses for the emergence of silicification include co-evolution with mammalian grazers and the role of environmental factors, such as high temperatures, drought, and low atmospheric $CO_2$ levels (de Tombeur et al., 2023). Here, we combine laboratory experiments, field studies and analysis of existing databases to test the role of temperature on the expression and emergence of silicification in terrestrial plants (Pang et al., 2025a). Firstly, the results of laboratory experiments show that Si is beneficial for plant under high temperature stress (40°C), but harmful under low temperature (0°C), whilst a 2°C increase results in a 37% increase in leaf Si concentrations. We then find that, globally, the average distribution temperature of high-Si plant clades is 1.2°C higher than that of low-Si clades. Across China, leaf Si concentrations increase with temperature in high-Si plants (wheat and rice), but not in low-Si plants (weeping willow and winter jasmine). From an evolutionary perspective, 77% of high-Si families (>10 mg Si $g^{-1}$ DW) originate during Earth warming episodes, while 86% of low-Si families (<1 mg Si $g^{-1}$ DW) originate during cooling episodes. On average, Earth's temperatures during the emergence of high-Si families are 3°C higher than low-Si families. Taken together, our evidence suggests that plant Si variation is closely related to global and long-term climate change. These findings on the link between plant silicification and changes in the Earth's temperature provide new clues regarding the interactions between Si and C cycling over geological timescales. In the future, we aim to further refine the interaction model among plant silicification, carbon cycling, and global temperature (Pang et al., 2025b). This model can be decomposed into the following cascading processes: First, the elevated atmospheric $CO_2$ concentration leads to global warming, and such a climatic context is likely to facilitate the emergence and expansion of high-silicon plants. These plants possess a strong capacity to absorb large amounts of monosilicic acid from the soil, which will promote silicate weathering. The cations released through silicate weathering will sequester $CO_2$ in the form of carbonates, which in turn exerts a negative feedback effect to reduce global temperature.

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# Land-use change mediated associations among soil environmental factors, microbial networks, and soil multifunctionality: A case study of the Changchong River small watershed in Chaohu Lake

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## ABSTRACT

Land-use change (LUC) is a core driver of dynamics in soil ecological function. Despite this, significant knowledge gaps remain regarding the variation of soil multifunctionality (SMF) across different LUC types, the relative contributions of soil environmental factors and microbial traits to SMF, and the identification of key drivers. This study focused on the Chaohu Lake basin in the middle-lower reaches of the Yangtze River. The impacts of LUC on soil microbial traits (diversity, network complexity and stability), physicochemical properties, mineral elements, and enzyme activities were investigated based on three land use types (grassland, cropland, and forestland). SMF was quantified using 26 indicators to identify its key drivers. The results demonstrated that after the conversion of cropland to forestland, soil properties and microbial community composition showed recovery toward a state similar to that of grassland, although microbial diversity decreased. Phosphorus could drive microbial community shifts. Trends toward recovery were also observed in microbial network complexity and stability, whereas only bacterial network stability increased significantly. Bacterial community assembly in grassland involved deterministic and stochastic processes. However, other land-use types primarily depended on stochastic processes, and total potassium served as a core driver of assembly. Cropland displayed the highest SMF, while the SMF of forestland recovered toward grassland levels. The drivers of SMF varied between soil layers. To be specific, physicochemical factors were predominant in the 0-20 cm layer, while chemical and mineral factors jointly drove SMF in the 20-60 cm layer. Notably, microbial network complexity emerged as a crucial microbial regulator of SMF. In general, reduced anthropogenic disturbance facilitated the recovery of SMF in forestland. In this study, knowledge gaps regarding SMF and LUC in the Chaohu Lake basin are addressed. Furthermore, this study underscores the critical role of microbial network complexity, elucidates the layer-specific differentiation of key drivers, and provides empirical insights for formulating ecological policies targeting regional land-use pattern optimization.

# Soil organic carbon fraction mediated microbial community assembly along stand age and seasonal gradients in temperate poplar plantations

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## ABSTRACT

Despite harboring the largest forest carbon stocks, soil carbon persistence is mainly controlled by microbial regulators. However, there are large uncertainties about the mechanisms of microbial community ecology interaction with soil carbon speciation. In this study, we sampled soils from temperate Populus (*Populus euramevicana* cv.'I-214') Plantations of four different stand ages (3, 6, 10, and 13 years) for three seasons (spring, summer, and autumn). Through integrated analyses, including high-throughput sequencing, co-occurrence network construction, null and neutral modeling, and assessments of soil physicochemical properties, we found that stand age, season, and the interaction between them significantly affected soil organic carbon (SOC), easily oxidizable organic carbon (EOC), particulate organic carbon, mineral-associated organic carbon, and recalcitrant organic carbon (ROC) ($P < 0.001$), while dissolved organic carbon was not affected. During summer, all fractions of carbon except EOC increased in trend with stand age. Afforestation improved bacterial diversity and richness, and age-related changes in bacterial community composition ($P < 0.001$) were dominated by stochastic assembly processes, most likely in spring, mediated by soil pH, SOC, ROC, cellulase activity, and C/P ratio. In contrast, fungal community composition was strongly affected by seasonal variation ($P < 0.001$) through deterministic assembly processes, which were weakest in spring, and showed greater dispersal limitation than bacterial communities. Specific microbial modules were a significant predictor for different carbon fractions ($P < 0.05$). Stand age favored the accumulation of stable organic carbon, while seasonal variations enhanced the consumption of labile organic carbon. Overall, this study emphasizes divergent microbial assembly - carbon linkages along stand age and seasonal gradients and highlights the critical role of microbial community assembly in soil carbon sequestration and stabilization.

# Microbial intra- and extracellular phosphorus recycling in response to global imbalanced soil nutrient changes

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**ABSTRACT**

A global stoichiometric crisis is raising with increasingly higher availability of carbon (C) and nitrogen (N) relative to phosphorus (P) from various human-induced inputs and depletion of P-containing minerals; this promotes microbial P strategies shifts from acquiring to recycling. However, the component-specific P incorporation under varied nutrient availability remain unclear, which is an intriguing issue with broad consequences for microbial P (re-)cycling. We quantified P incorporation into microbial DNA and phospholipids by 33P labeling under four contrasting conditions (low/high P soil × low/high CNP addition). We found preferential P allocation to microbial DNA and phospholipids for P-rich and P-poor soils, respectively. P incorporation rate and turnover of the two P pools can be intensified by C availability via shifting microbial composition towards a stronger representation of their functional traits. Our results suggest that phospholipid can serve as a variable P storage to be potentially depleted via intracellular recycling under strong P limitation, which can "conserve" the microbial P cycling, aggregate soil P depletion and increase plant-microbial competition under global changes.

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# Soil Carbon and Soil Health Across a Prairie Restoration Chronosequence in Southern Wisconsin

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## ABSTRACT

Prairie restoration, defined as the re-establishment of native prairie vegetation and disturbance regimes on lands previously converted to agriculture or other intensive uses, is widely adopted as a strategy to enhance soil carbon sequestration and improve soil health. However, empirical evidence linking restoration age to soil physical and biogeochemical properties remains limited, particularly across landscapes with complex land-use histories. In this study, we examined soil carbon stocks and soil health indicators across a prairie restoration chronosequence in southern Wisconsin, USA.

We sampled soils from prairie sites restored at six time points spanning 1987 to 2024, along with two remnant prairies and one agricultural References site. Sites were located in close geographic proximity to minimize variation in climate and parent material. At each site, soil water infiltration was measured *in situ*, replicated soil cores were collected to 30 cm depth (partitioned into 0-10 cm and 10-30 cm increments), and soils were analyzed for soil carbon and nitrogen concentration and stocks, microbial biomass carbon (via chloroform fumigation-extraction), and selected soil physical and chemical indicators including bulk density, pH, and cation exchange capacity.

This study aims to evaluate how soil carbon stocks, microbial biomass, and soil physical properties vary with time since prairie restoration. We further examine the extent to which restored prairies converge toward remnant prairie soil conditions, and whether legacy effects of previous agricultural use persist across soil depths.

By integrating soil biogeochemical and physical measurements across sites with contrasting restoration chronosequence, this work seeks to improve understanding of soil recovery trajectories following prairie restoration. The findings will provide insights relevant to prairie restoration strategies and contribute to assessments of restored grassland as long-term carbon sinks.

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# Decadal Spatiotemporal Dynamics of Boreal Soil Chemistry in Response to Industrial Atmospheric Loading

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**ABSTRACT**

Atmospheric deposition from industrial activity in the Athabasca Oil Sands Region (AOSR) of Alberta, Canada, poses a significant threat to boreal forest health. While the Wood Buffalo Environmental Association's (WBEA) Forest Health Monitoring (FHM) program has tracked these impacts since 1998, the long-term response of soil chemistry remains poorly understood. This study analyzes a 13-year (2011 – 2024) dataset from 12 unburnt FHM sites located at different distances from major emission sources. Soil samples from the forest floor (LFH) and three mineral soil layers (0 – 5, 5 – 15, and 15 – 30 cm) were collected across three sampling events (2011, 2018, and 2024) and analyzed for chemical properties. Mixed-effects models were employed to assess temporal trends, spatial gradients, and the distribution of total C, S, and N; bioavailable N, S, and P; pH; and exchangeable basic cations and Al. Results indicate that spatiotemporal trends were more pronounced in the LFH than in mineral horizons. In the LFH, extractable S, $SO_4$-S, $NH_4$-N, and exchangeable Ca were 37%, 46%, 79%, and 18% lower in 2024 than in 2011, respectively. Spatially, total S, pH, Ca, Mg, and BC:Al ratios in the LFH were significantly higher at sites closer to emission sources. Conversely, across all mineral layers, total C increased by 40% over the study period. Critically, no evidence of soil acidification was observed, even at high-deposition sites, due to the significant buffering capacity provided by basic cations. This long-term perspective is essential for predicting ecosystem resilience and formulating science-based policies to protect the boreal forest amidst ongoing industrial activity.

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# Geographic variations and multiple drivers of soil organic carbon stability in larch plantations

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**ABSTRACT**

Clarifying the distribution patterns and drivers of soil organic carbon (SOC) and its labile fractions is essential for evaluating forest carbon sinks. Larch, which is widely distributed across northern China and has strong environmental stress tolerance, exhibits unclear SOC spatial variation pattern in its plantations. We hypothesized that soil properties act as direct drivers, whereas geographic and climatic factors exert indirect effects via hydrothermal conditions. Based on 0–30 cm soil samples from 41 sites, we examined the spatial variations and multiple drivers of SOC, particulate organic carbon (POC), easily oxidizable organic carbon (EOC), and dissolved organic carbon (DOC). Combined with random forest and structural equation modeling, we disentangled the multi-scale driving factors and regulatory pathways of these carbon fractions. Results showed that SOC and labile fractions decreased with soil depth and exhibited clear latitudinal and longitudinal gradients, SOC and EOC increasing along both latitude and longitude. EOC (7.55 ± 0.45 $g \cdot kg^{-1}$) and POC (5.24 ± 0.52 $g \cdot kg^{-1}$) were the dominant fractions, whereas DOC (0.132 ± 0.008 $g \cdot kg^{-1}$) accounted for the smallest proportion. SOC had a synergistic relationship with EOC and POC, but exhibited an inverted U-shaped relationship with DOC. Soil nitrogen and phosphorus were key direct drivers of SOC, POC, and EOC variations. Geographic factors, particularly latitude, strongly influenced POC and DOC through effects on hydrothermal conditions such as the mean annual temperature and precipitation. Overall, soil properties served as direct intrinsic drivers, whereas geographic and climatic factors and stand characteristics operated mainly through indirect pathways by regulating carbon input and decomposition. This study reveals the synergistic regulation of SOC stability in larch plantations by multiple environmental factors, clarifying the differential regulatory mechanisms of SOC and its labile fractions along a geographic gradient. These findings provide a scientific basis for enhancing soil carbon sequestration in larch plantations.

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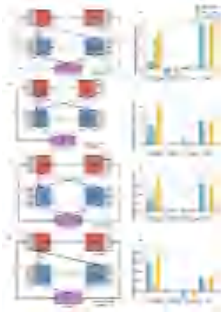


**FIGURE** Structural equation models quantifying the effects of environmental factors on SOC and its labile fractions. (a–d) Final SEMs for SOC, POC, EOC, and DOC, respectively. (e–h) Standardized path coefficients for the corresponding models. All the models exhibited good fit ($0 \leq$ Fisher’s $C/df \leq 2$ and $0.05 < P \leq 1.00$). Asterisks indicate path significance: $*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

# Spatial Characteristics of Soil Organic Carbon in Forests of China

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**ABSTRACT**

In the context of global efforts to address climate change, China has made an active commitment to achieving carbon neutrality before 2060. As a vast country with significant regional variations in topography, climate, soils, and forest types, China has also undergone one of the world's largest forest restoration initiatives in recent decades. These combined factors have profoundly altered and improved the quality of forest soils across the nation. However, the remarkable spatial heterogeneity of China's forests introduces substantial uncertainty in estimating forest carbon sequestration potential and emission reduction capacity. Therefore, it is urgently necessary to obtain comprehensive baseline information on forest soils at the national scale, particularly regarding soil organic carbon (SOC).

Over more than a decade of effort, China has completed its first relatively systematic national forest soil survey, revealing key soil properties including bulk density, pH, organic carbon, total nitrogen, total phosphorus, total potassium, available potassium, and available phosphorus. Based on the 1:250,000 forest vegetation distribution database—covering 2.35 million forest polygons—together with 40 covariates in five categories (at 200 m spatial resolution) and 8,304 forest soil SOC samples collected from 31 provinces, municipalities, and autonomous regions between 2015 and 2023, a spatial model and digital soil mapping techniques were applied to simulate and map the spatial distribution of forest SOC. By integrating gravel content and bulk density data from soil profiles, SOC density was estimated across soil layers. Combined with China's 2021 national forest inventory data, the national forest soil organic carbon storage and its spatial characteristics were quantified.

The results showed that the mean SOC density within the top 100 cm of forest soils in China was 139.00 t/ha, with the highest values observed in the Southwest (167.38 t/ha) and Northeast (156.57 t/ha) regions. The total forest SOC storage was estimated at 27.78 Pg C, with the Southwest and Northeast contributing 34.75% and 18.86% of the total, respectively. This investigation provided the first comprehensive national baseline dataset of China's forest soil information, offering valuable support for the development of forest management strategies and for improving the scientific estimation of forest soil carbon stocks under the global climate change context.

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# Mechanisms of soil organic carbon accumulation under green manure cover in citrus orchard

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**ABSTRACT**

Living green manures are widely recognized as an effective practice for enhancing soil organic carbon (SOC) in orchard ecosystems, yet the underlying accumulation pathways remain poorly understood across soil textures. To elucidate these mechanisms, we conducted field experiments in citrus orchards with living smooth vetch (*Vicia villosa* var. *glabresens*) cover and clean tillage under two contrasting soils: sandy loam and silty clay loam. We also used a microcosm experiment with isotope labeling to quantify SOC fractions and the C source and fate in root, mycelium, and coexistence pathways under citrus–vetch intercropping versus citrus and vetch monocropping.

In sandy loam, vetch cover markedly increased particulate organic carbon (POC, 106~239%) and mineral-associated organic carbon (MAOC, 43~243%), leading to a 232% rise in surface SOC. In silty clay loam, SOC increased by 19% in the topsoil through modest POC (13%) and MAOC (4%) gains, while MAOC within deeper layers showed a declining trend. In sandy loam, vetch cover enhanced microbial carbon pump (MCP) efficiency via greater nutrient availability, clay and mineral factors, driving microbial necromass C contributions to both POC and MAOC. By contrast, in silty clay loam, POC accumulation was mainly plant-derived C but diluted microbial contributions with in topsoil (ΔMCP efficiency < 0); MAOC in deeper layers tended to destabilize due to MCP efficiency being constrained by elevated mineral protection and phosphorus availability.

Vetch cover increased both vetch- and citrus- derived C in POC by 10.83%, but decreased citrus and native SOC in MAOC by 46.72% via the root pathway. Through the mycelium pathway, vetch C was retained in POC (3.25%) and MAOC (0.23%), while 92.04% of citrus C was stabilized in MAOC, resulting in a 1.4 fold increase compared to citrus (64.9%) and vetch (66.6%) monocultures. Under vetch cover, root–mycelium pathways increased rhizosphere MAOC by 45.5%, which was 1.9 times higher than citrus monoculture (15.6%) and exceeded the combined effect of citrus and vetch monocultures (24.6%), resulting in a 56.6% net SOC gain. Distinct C and N allocation from vetch via root and mycelium activated r-strategists (gram-negative bacteria) and k-strategists (saprotrophic fungi) microbial groups to preferentially assimilate recent photosynthate, respectively, enhancing microbial carbon use efficiency and amino sugar accumulation efficiency. This reduced the priming effect and promoted C stabilization across SOC pools in distinct forms.

Overall, vetch cover markedly enhanced SOC accumulation, but the dominant mechanisms differed by soil texture and pathway. Citrus–vetch interactions strengthened mycelium-mediated MAOC formation, achieving a synergistic "1 + 1 > 2" effect on SOC stabilization. These findings underscore the need to tailor green manure management to soil texture to optimize carbon sequestration and ecosystem sustainability in perennial orchard systems.

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# Fire-derived charcoal enhances soil ecological functions and recovery in subtropical forest plantations

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## ABSTRACT

Fire-deposited charcoal is a widespread and long-lasting component of fire-affected ecosystems, yet its ecological roles in subtropical forest soils remain insufficiently explored. Through a series of long-term field-based charcoal manipulation experiments in *Pinus massoniana* plantation timber harvest sites in southern China, we examined how varying amounts of fire-derived charcoal influence soil microbial communities, nutrient dynamics, and carbon (C) stability following broadcast burning. Results consistently demonstrated that charcoal significantly alters key aspects of soil ecological functioning across multiple temporal scales. One year after charcoal application, a taxon-specific shift in the relative abundance of soil bacterial and fungal genera was observed, although overall microbial diversity remained unaffected. Soil pH emerged as the dominant factor regulating bacterial abundance and diversity, while available phosphorus also contributed to structuring microbial community composition. Five years after burning, 11 out of 32 measured soil indicators—including soil organic matter (SOM), microbial biomass carbon, and enzyme activities—differed significantly among treatments. Plots with higher charcoal inputs effectively alleviated fire-induced soil degradation, restoring soil organic matter and microbial properties to levels comparable to the unburnt control, whereas plots with reduced charcoal inputs showed limited recovery and remained degraded. Seven years after treatment, charcoal continued to exert beneficial effects on soil C stabilization. Although it did not alter dissolved organic C, charcoal markedly enhanced microbial C assimilation, the C pool management index (CPMI), and the proportion of soil organic C associated with small, stable aggregate fractions (<0.05 mm) at the surface layer (0–10 cm). MBC was also elevated in deeper soils (10–20 cm) of charcoal-amended plots, indicating a depth-dependent response. Collectively, these studies reveal that fire-derived charcoal contributes to soil quality recovery, microbial reorganization, and long-term C stabilization in subtropical forest plantations. By improving soil chemical balance, promoting microbial functionality, and facilitating the incorporation of organic C into stable aggregates, charcoal serves as an essential ecological legacy of fire that enhances post-disturbance soil resilience. These findings underscore the importance of managing charcoal generation and retention in broadcast burning practices to sustain soil health and support ecosystem restoration in subtropical plantation forests.

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# Aggregate-mediated mechanisms of soil carbon and greenhouse gas emission under green manure cover in citrus orchard

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**ABSTRACT**

Living green manures are recognized as an effective strategy to enhance soil organic carbon (SOC) storage and improve soil quality in orchard ecosystems. However, the underlying mechanisms linking soil aggregate stability, carbon stabilization, and greenhouse gas (GHG) emissions under long-term cover cropping remain unclear. To address this knowledge gap, this study investigated citrus orchards in the Three Gorges Reservoir area to explore how long-term legume cover cropping reshapes soil aggregate structure and carbon stabilization processes, and how these structural and biochemical changes jointly regulate $N_2O$ emissions.

Clean tillage (CK) and smooth vetch (*Vicia villosa* Roth var. *glabresens* Koch) cover cropping maintained for 4, 6, 7, 10, and 11 years were compared. Soil aggregates were fractionated into large macroaggregates (LMA, 2–8 mm), small macroaggregates (SMA, 0.25–2 mm), and microaggregates (MIA, <0.25 mm), and their carbon fractions were analyzed through field sampling and laboratory incubation experiments. The results showed that, long-term smooth vetch coverage significantly increased LMA (3.63%–34.35%) while reducing SMA and MIA fractions (4.35%–27.09% and 18.22%–59.86%), and enhanced both particulate (fPOC, oPOC) and mineral-associated organic carbon (MAOC). These changes indicated a transformation of labile carbon into more stable forms, with calcium ions and pH identified as key regulators of MAOC formation. PLS-PM analysis showed that aggregate stability and the fPOC/MAOC and oPOC/MAOC ratios contributed to SOC increases of 41.46%–117.32%.In parallel, smooth vetch cover significantly increased mean $N_2O$ and $CO_2$ emission fluxes, but emissions declined after 11 years as aggregate stability improved. Aggregate size significantly influenced GHG fluxes ($p < 0.001$), and PLS-PM results revealed that cover duration regulated $N_2O$ emissions via three main pathways: modulating soil moisture, enhancing water-stable aggregate stability (W_MWD), and optimizing the microbial C:P threshold elemental ratio (TER C:P).

Together, these findings demonstrated that long-term legume cover cropping enhances both structural and chemical stability of soil carbon, thereby achieving dual benefits of SOC sequestration and GHG mitigation. This integrated understanding provides a scientific basis for sustainable orchard management and climate-smart agricultural practices in subtropical regions.

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# Phosphorus Limitation and Adaptation Strategies for Productivity Formation of Pinus massoniana Plantations in China

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**ABSTRACT**

China has the largest area of plantations globally, contributing to 25% of the global increase in green area. However, improving the productivity of these plantations remains a core challenge. Phosphorus (P), an essential element for plant growth and metabolism, plays a critical role in energy storage, transfer, and transformation. In China, planted forests (e.g., *Cunninghamia lanceolata*, and *Pinus massoniana*) are predominantly distributed in subtropical regions where available P levels are low, significantly impacting forest productivity. This study addresses two primary issues: (1) Is the productivity of *P. massoniana* plantations limited by soil P availability? (2) How does this species respond to low P (that is P limitation) during its growth cycle? The data comes from two aspects: literature data (1990-2019) and survey data (2012-2019).

We found that over 85% of the surveyed sites exhibited deficient levels of total P and available P, indicating P deficiency as a major factor determining soil fertility in *P. massoniana* plantations. Spatially, total P levels were higher in eastern, northern, and southern regions of subtropical China, while available P was more abundant in eastern and northern regions. Vertically, available P decreased with soil depth. With the increasing latitude, leaf N:P ratio and soil acid phosphatase (ACP) activity increased, indicating P limitation even at high latitude. Increased soil ACP activity compensated for P deficiency, while high N:P ratios (>16, a threshold for P limitation) in needles reflected P stress. Multiple regression models demonstrated that soil total P significantly influenced the annual net primary productivity of *P. massoniana* plantations, explaining 8-35% of the variation. Structural equation models accounted for 11-13% of ANPP variation, highlighting indirect effects of soil total P on productivity through root P uptake. Soil available P consumption transitioned to accumulation at around 30 years of stand age. With increasing age, the N:P ratios of all organs (except the branches and the current year leaves) >16, and showed an increasing trend. Also, soluble sugar/ starch ratio increased first and then decreased in the coarse roots, and the maximum value was reached at 37 years. Soil available P and ACP activity significantly increased after 28 years of age, while soil enzyme-P decrease at the same age.

In conclusion, the planted forests of *P. massoniana* in subtropical China suffer from severe P deficiency, which is the key limiting factor for productivity. The degree of P limitation increases initially and then decreases over the growth cycle, peaking at 37 years. This tree species employs two main strategies to cope with P limitation: physiological absorption strategies involving internal P mobilization and reduced trunk growth in older stands, and soil P utilization strategies enhancing ACP production to improve P availability.

**Acknowledgments**

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# Sensitivity of biochar-root interaction on the subtropical forest increase of sink and reduction of emission

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**ABSTRACT**

Recent studies have shown that biochar by artificially adding is a reliable method to reduce atmospheric carbon dioxide concentrations. Stable biochar alters soil structure, water absorption, and microbial activity, which in turn affects the short-term turnover of natural soil organic carbon through the priming effect. However, there is a knowledge gap regarding how biochar influences the direction, persistence and magnitude of the priming effect on soil native organic carbon, as well as the underlying microbial response mechanism. The objectives of the study are to investigate the priming effect of biochar on natural soil respiration, soil respiration temperature sensitivity, soil microbial diversity, microbial community structure, enzyme activity and carbon source utilization under different biochar dosages. These findings will help clarify the soil carbon self-circulation model and provide a scientific basis for subtropical management of subtropical bamboo forest. To understand the interaction effects of biochar-root in forest trees, we examined the root morphology and soil microbial community on moso bamboo plantations (*Phyllostachys edulis*) as well as one-year old its seedlings with four biochar addition treatments (control: CK 0 $t \cdot hm^{-2}$,low biochar: LB 5 $t \cdot hm^{-2}$, medium biochar: MB 10 $t \cdot hm^{-2}$ and high biochar: HB 20 $t \cdot hm^{-2}$). The results showed that biochar addition decreased the soil respiration rate, and this decrease became smaller as the biochar dosage increased. Compared with CK, the mean soil respiration rate in LB, MB and HB decreased 2.33%–54.72%, 1.28%–44.21% and 0.09%–39.22%, annual mean soil moisture increased 0.62%–75.58%, 0.87%–48.18% and 0.68%–74.73%, respectively. Compared with control, total microbial biomass in 0-10 cm increased 9.1% and 3.5% after the first and the second year' biochar addition for LB, increased 22.0% in the first year and decreased 9.0% in the second year for MB, both increased 7.1% and 7.8% for HB. Biochar addition significantly decreased Chao abundance, Shannon's indicator of bacteria in HB, and increased Simpson's indicator of bacteria in HB, microbial biomass at 10–20 cm soil, polyphenol oxidase activity, invertase and urease activity at 0–10 cm soil. Annual cumulative soil respiration was significantly and positively correlated with the biomass of total PLFAs, gram-negative bacteria, bacteria, and arbuscular mycorrhizal fungi ($P < 0.05$) at 0–10 cm soil. The contribution of the decomposition of biochar-self to soil carbon mineralization was 0.8%–1.1%, root contribution for that increased 3.1%–4.0%. In conclusion, low biochar addition significantly decreased soil carbon emission by increasing microbial biomass and soil enzyme activity at 10–20 cm depth. It also altered the microbiological community structure and biodiversity, which lays the foundation for long-term forest ecosystem C sequestration in forest ecosystems and provides a practical References for climate change mitigation.

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# Multi-trophic biodiversity regulates decomposition and mitigates drought effect

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**ABSTRACT**

The decomposition of organic matter is a major determinant of the biosphere – atmosphere carbon feedbacks and ecosystem nutrient recycling. Decomposition depends on the characteristics and diversity of plant-produced organic matter as the primary energy source, and is further regulated by an astounding diversity of soil organisms ranging from prokaryotes to macro-invertebrates that are organized in highly complex food webs. It can also be indirectly regulated by plant canopy driven modifications of micro environmental conditions. However, the complexity of interactions across trophic levels has made it difficult to quantify how biodiversity regulates ecosystem processes. Furthermore, simultaneous climate and biodiversity change are of particular concern, because biodiversity may contribute to ecosystem resistance and resilience and may mitigate climate change impacts. Yet, the extent and generality of how climate and biodiversity change interact, remain insufficiently understood. Here we show a regional study by manipulating diversity from litter to decomposer across stands of tree diversity gradients, to disentangle the complex interaction multi-trophic diversity. We show litter diversity consistently accelerating decomposition, which could be further facilitated by decomposer diversity. Tree diversity also indirectly facilitates the complementarity of decomposition with favoring microenvironment and decomposer activity. Furthermore, with an inter-biome experiment, we tested here how biodiversity in the multi-trophic decomposer system drives decomposition in forest ecosystems under drier conditions. Our results show at a relevant spatial scale covering distinct climate zones that forest floor biodiversity across trophic levels has a strong potential to mitigate drought effects on C and N dynamics during decomposition. Preserving biodiversity at multiple trophic levels contributes to ecosystem resistance and appears critical to maintain ecosystem processes under ongoing climate change.

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# Managing Forest Soil Carbon to Preserve Climate and Biodiversity

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**ABSTRACT**

A shared future for humanity requires enhancing human well-being within a healthy environment. This can be achieved by promoting sustainable development through efficient soil management that enables carbon storage across diverse ecosystems worldwide. This study summarizes three decades of research on soil organic matter (SOM) management in forest and related systems in the eastern Amazon (Brazil) and the Congo Basin. Effective soil management is essential for climate change mitigation, food security, land restoration, and biodiversity conservation, as demonstrated by long-term studies in forest and pasture ecosystems of the Brazilian Amazon, and in forest plantations, agroforestry, and fallow systems in the Congo Basin.

Pasture establishment and afforestation generally increase soil organic carbon, particularly in topsoil, as observed in 17-year-old pastures in the Brazilian Amazon and in mixed forest stands in the Congolese coastal plains, thereby contributing to climate mitigation. However, over time, SOM quality becomes more labile-both in Amazonian pastures and in Congo Basin plantations (five years into the second 7-year rotation)-potentially reducing long-term carbon storage benefits. These findings highlight limitations in achieving certain Sustainable Development Goals (Agenda 2030) and underscores the need for improved management strategies.

Ecosystem management tailored to local environmental resilience can enhance carbon storage and associated co-benefits, supporting healthy soils, ecosystems and humans. For example, legumes improve soil fertility, particularly nitrogen availability, and enhance bacterial and fungal communities compared with non-leguminous species. However, species selection is critical, as some legumes, such as *Calliandra*, may produce lower yields than natural fallows dominated by *Chromolaena*, which is better adapted to acidic soils. Biodiversity may also be threatened by invasive species: *Chromolaena* often performs well, whereas *Acacia mangium* increases carbon and nitrogen stocks and improves phosphorus availability in topsoil but carries a high risk of invasiveness. Its use therefore requires careful risk assessment prior to implementation.

Overall, managing carbon through appropriate tree-based ecosystem strategies can promote climate change mitigation and biodiversity conservation, ensuring long-term ecosystem sustainability and human well-being.

**Keywords:** Soil, Climate mitigation, Resilience, Biodiversity, Human well-being, Sustainable Development

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# Influence of species diversity and soil cementing substances on the stability of agglomerates in three forest types of Zhangguangcailing Mountains

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**ABSTRACT**

Vegetation composition is an important factor driving changes in soil function in forest ecosystems. In order to investigate the effects of community characteristics and soil cementitious substances on soil aggregate stability in different forest types in Zhangguangcailing mountains, we compared the changes in soil aggregate stability and the differences in the content of cementitious substances in three typical forest types in Zhangguangcailing mountains (dark coniferous forests, mixed spruce coniferous forests, and montane poplar birch forests); analyzed the effects of organic and inorganic cementitious substances on aggregate stability; and explored the mechanism of the role of community characteristics on aggregate stability using the partial least-squares throughput model. The effects of organic and inorganic cementitious substances on the stability of aggregates were analyzed, and the mechanism of community characteristics on the stability of aggregates was investigated using the partial least squares throughput model. The results showed that (1) the particle size of aggregates in the three forest types was mainly concentrated in the range of 2-0.25 mm, and the soil aggregate stability of the mixed conifer forest was significantly higher than that of the other two forest types. (2) Compared with the dark coniferous forests, the total organic carbon of the mixed conifer forests and the mountain poplar birch forests were 57.1% and 44.2% higher, the total particulate organic carbon was 56.9% and 48.4% higher, and the total mineral-bound organic carbon was 66.3% and 71.3% higher, respectively. The above three kinds of organic carbon contents in the dark conifer forest were significantly lower than those in the other two forest types ($P$<0.05); (3) the complexed state of iron oxides showed that the mountain poplar birch forest > cloudy fir mixed conifer forest > dark conifer forest, and the amorphous form of iron oxides and free iron oxides did not have any significant difference among the soil layers ($P$>0.05). (4) Partial least squares throughput modeling showed that community characteristics had a direct highly significant negative effect on iron oxide content (throughput coefficient of -0.459, $P$ ≤0.001), and a direct positive effect on organic carbon, but not significant ($P$>0.05). Soil iron oxide had a significant positive effect on soil organic carbon (throughput coefficient of 0.349, $P$≤0.1) and a positive but non-significant effect on aggregate stability. Soil organic carbon had a highly significant positive effect on soil aggregate stability (throughput coefficient of -0.693,$P$≤0.001). In summary, soil aggregate stability was highest under mixed spruce-fir forest; organic cementitious materials played a direct role in soil aggregate stability, and inorganic cementitious materials played a role as an indirect factor; the influence of different forest types on aggregate stability was mediated by cementitious materials, and changes in forest type directly affected the inorganic cementitious materials in the soil, and the inorganic cementitious materials directly affected the accumulation and transformation of organic cementitious materials, thus affecting aggregate stability. Inorganic cementitious substances directly affect the accumulation and transformation of organic cementitious substances, which in turn affects the stability of aggregates. Therefore, the upper layer of vegetation can mediate the state of iron oxides, affect its interaction with soil organic carbon, and ultimately have an impact on the aggregates. This study can provide a theoretical basis for revealing the coupling relationship between the stability of forest dark brown soil aggregates and cementing materials.

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# Responses of selected soil physical properties to early stages of active ecological restoration in the Mistbelt forest of South Africa

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**ABSTRACT**

Forest degradation caused by human activities, invasive species and previous land use has led to a decline in soil physical quality and ecosystem functioning in Mistbelt forests. Active ecological restoration has been implemented to address this decline through the planting of indigenous tree species, yet there is limited data on how short-term restoration affects soil physical properties. The study evaluated the early impacts of restoration on soil physical and hydraulic properties across three Mistbelt forest sites. It was arranged in a 2 x 3 factorial design, with factors comprising two statuses (restoration and References) and three gradients partitioned into blocks, which were replicated 10 times. A two-way analysis of variance was used to analyse soil properties including soil bulk density (BD), total porosity (TP), soil moisture content (MC), mean weight diameter (MWD), glomalin-related soil protein (EE-GRSP), aggregate stability, etc. Results demonstrated that the most improved responses were observed in Izingcuka, as compared to the Swallowtail and Madonna and Child sites. At Swallowtail restoration, the results showed slightly elevated BD (1.24 g $cm^{-3}$), lower TP and lower MC (13%) than References site. This was likely due to previous land disturbances, including deforestation and soil compaction. The soils across the study were generally fine-textured soil, with high clay and silt content. This further explain the lower soil porosity and limited soil moisture availability observed. At the Zingcuka restoration site, MWD (3.44) and MC (63%), were notably higher, reflecting stronger aggregates stability and reduced water loss. In contrast, the Madonna and Child sites showed a more variable pattern, with increase in water content but had signs of restricted pore development and slower infiltration. No significant difference was observed ($p > 0.05$) in EE-GRSP, suggesting that the changes in soil structure are mainly driven by physical factors, such as such as clay content rather than restoration activities. Overall, the findings indicate that active forest restoration contributed to improvements in soil physical conditions, though the extent of recovery differs between sites and are still in their early stages.

**Keywords:** Forest degradation; Soil bulk density; Soil porosity; Soil structure; Soil recovery

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# Resistance and Resilience of Soil Microbial Communities to Forest Degradation and Their Role in Carbon Sequestration in Dry Tropical Forests

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**ABSTRACT**

Tropical dry forests (TDFs) are biodiversity hotspots and provide essential ecosystem services, yet they are among the most threatened biomes globally due to deforestation, overgrazing, and climate change. Soil processes in TDFs remain poorly understood, particularly regarding how chronic anthropogenic disturbances (CAD) alter microbial-mediated carbon and nutrient cycling. The TRILOBITE project addresses this knowledge gap by investigating the resistance and resilience of soil microbial communities to CAD-induced degradation and their role in soil organic carbon (SOC) sequestration during natural one year regeneration in the Tumbesian dry forests of southwestern Ecuador.

Our study combines a replicated degradation gradient with grazing exclusion plots to disentangle the effects of disturbance and recovery. We integrate the study of plant-soil feedbacks (PSFs), microbial community composition changes, and SOC fractionation using complementary approaches: ecophysiological indicators (fungi:bacteria ratio, metabolic quotient, microbial biomass C), litter decomposition assays, and high-throughput sequencing to assess phylogenetic diversity in bulk and rhizosphere soils. SOC pools were quantified through conventional fractionation and Vis-NIR spectroscopy to enable scalable monitoring.

Our results showed that SOC and mineral-associated organic matter (MAOM) decline significantly with CAD, accompanied by reductions in nitrogen and phosphorus and lower C:N ratios, indicating impaired nutrient retention. Aggregate stability showed no significant differences along the gradient, though a decreasing trend was observed with degradation. Microbial activity remained relatively stable across degradation stages, but fungal and bacterial alpha diversity decreased under disturbance. Notably, fungal community structure was strongly influenced by degradation and seasonality, whereas bacterial communities were less responsive. These patterns suggest that fungi may serve as sensitive indicators of ecosystem resilience thresholds.

Our findings emphasize the vulnerability of TDFs to CAD and highlight the importance of managing disturbance regimes to enhance soil carbon storage and biodiversity. By linking microbial traits to SOC dynamics, this research provides actionable insights for sustainable soil management, restoration planning and climate change mitigation through improved land stewardship in tropical dry forests.

**Keywords:** soil carbon sequestration, tropical dry forests, grazing, plant-soil feedbacks, phylogenetic diversity.

**Acknowledgments**

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# Burn history and residue solubility influence the transformation of pine litter in forest soils

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## ABSTRACT

The fate of litter-derived carbon (C) inputs into forest soils determines soil nutrient cycling and C accrual, which in turn sustains ecosystem productivity and resilience. Forest soil C cycling is influenced by various factors, such as microbial substrate availability and nutrient demand. Further, wildfire can alter these C and nutrient cycles, affecting how litter-derived C is transformed and stabilized. To unravel the drivers of C stabilization in forest soils we performed a 72-day C-addition incubation, where we added different types of litter to soils with differing burn histories (50 years or 5 years since last burn), with and without additional inorganic nitrogen (N). $^{13}$C-labelled pine needle litter was added whole or after fractionation into structural and water-soluble components. The litter-derived C was traced to calculate soil priming and C-use efficiency (CUE). A CRDS analyzer was used to obtain high-temporal resolution $^{13}C$-$CO_2$ data throughout the course of the incubation. Priming was low in both soils, at times even negative. CUE was higher in the 50-year-since-burn soil compared to the CUE in the more recently burned soil. We found that CUE was highest with the labile litter fraction, which had the highest C:N ratio. Further, the addition of inorganic N had no effect on CUE or soil priming in either soil. These results suggest that C quality, but not necessarily N availability, was the primary driver of the fate of litter-derived C in these forest soils. Burn history also had a lasting impact on C cycling, with greater total C but less soil respiration and a lower CUE of added litter, demonstrating how wildfire can alter the fate of C inputs in forest soils.

# Developmental plasticity drives convergent shifts in phosphorus acquisition strategies toward root phosphatase activity in Moso bamboo under nitrogen addition

**Quan Li[1], Tianyi Hu[1], Lei Jiang[1], Hangxiang Ji[1], Jingchen Xie[1], Jing Chen[1], Shuangbo Bi[1] Man Shi[1], Tingting Cao[1], Zhikang Wang[1], Ximei Zhang[2], Xinzhang Song[1]***

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## ABSTRACT

Anthropogenic nitrogen (N) deposition is a major driver of global change. However, its effect on the developmental plasticity of plant nutrient strategies remains poorly understood. This is particularly critical in phosphorus (P)-limited subtropical forests, where N-induced shifts in biogeochemical cycles may intensify P constraints. Using Moso bamboo (*Phyllostachys edulis*) as a model system, we investigated the response of root P acquisition strategies and leaf P fractions to N addition at different developmental stages (young vs. mature). We identified a convergent shift in P-acquisition pathways in response to N addition: young bamboos transitioned from morphological (specific root length and area) to exudation-based strategies, whereas mature bamboos shifted from carboxylate-dominated to phosphatase-enhanced pathways. Ultimately, both stages converge during root phosphatase-mediated organic P mobilization. This strategic unification was also observed in the leaves: N addition significantly reduced inorganic P pools without altering structural P fractions (lipid-P, residual-P, and nucleic-P), indicating a prioritization of P for growth amid intensified limitation. The key drivers, including soil acidification, available P depletion, microbial biomass P accumulation, and root phosphatase activity, collectively influenced this root-leaf recalibration. By integrating specific root pathways and internal P fraction dynamics, our study advances the conventional "Get–Save–Return" framework, underscoring developmental plasticity as a central mechanism in tree responses to N deposition. These findings provide a new mechanistic understanding of nutrient cycling in subtropical forests under global climate change conditions.

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# Effects of different vegetation restoration measures on soil erosion resistance capacity on the typical watershed in the Three Gorges Reservoir Area

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## ABSTRACT

Vegetation restoration is a key ecological measure for reducing soil erosion. However, the direct and indirect regulatory mechanisms of different vegetation restoration measures on soil erosion resistance in the Three Gorges Reservoir Area (TGRA) remain unclear. Therefore, this study selected 7 types of vegetation restoration measures in Heigou watershed to quantifying soil physical and chemical properties, root traits, microbial community diversity, and separation capacity under different vegetation restoration types to clarifying the impact of vegetation restoration measures on soil erosion resistance. Meanwhile, combined with PLS-SEM, the direct and indirect regulatory mechanisms of biological and abiotic factors on soil erosion resistance were elucidated. The results showed that the soil contents of soil organic matter (SOM), total nitrogen (TN) and total phosphorus (TP) in tea plantation were significant higher than that in the other land uses. The root mass density (RMD) in bamboo forest was significant higher than that in the other land use types. The diversity of soil bacterial and fungal communities and soil aggregate stability were significantly higher in the mixed coniferous-broadleaf forest than in the other land use types. Different vegetation restoration measures significantly reduced soil separation capacity ($P<0.05$). Root traits and soil aggregate both had direct and significant negative effect on soil erodibility ($P<0.001$). Meanwhile, root traits had indirect and significant positive effect on soil aggregate by affecting the diversity of soil bacterial communities ($P<0.01$). Planting of plants with well-developed root system in the future can reduce soil erosion in the Three Gorges Reservoir area.

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# Cessation of nitrogen addition increased organic matter stability by decoupling carbon input and stabilization in a subtropical forest soil

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**ABSTRACT**

Nitrogen (N) deposition alters soil carbon (C) cycling through plant–microbial–mineral interactions; however, the evolution of soil organic carbon (SOC) pools in acid soil from N addition to N decline remains poorly understood. A decade-long field experiment in a subtropical acid soil—comprising seven years of N addition and three years of cessation—revealed that particulate and mineral-associated organic carbon (POC and MAOC) exhibit starkly contrasting dynamics. The POC pool and its proportion of SOC had a biphasic response to N addition and cessation: an initial decline (compared to control) with prolonged N addition exposure was followed by a recovery phase, a dynamic governed by plant-derived C inputs. This short-term (four-year) decline stemmed from N-induced microbial decomposition exceeding plant C inputs, reducing net plant-derived C. Recovery of the POC content to the control level during the long-term (seven-year) and post-cessation phases occurred through acidity-driven suppression of microbial decomposition, establishing a plant-derived C input-decomposition equilibrium. The MAOC pool and its SOC proportion continuously increased (2–17% vs control) during and after N addition, primarily driven by microbial necromass accumulation and increased mineral protection by iron and aluminum oxides. POC and MAOC shifted from coupling under short-term N addition to decoupling under long-term addition and after cessation, primarily due to asynchronous plant–microbial responses. Overall, our results confirmed that N addition leaves a positive legacy in MAOC that increases SOC stability, improving predictions for forest acid soils C dynamics under shifting N deposition regimes.

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# The effects of N deposition on the decomposition of C rhizodeposits and its underlying microbial mechanism in Moso bamboo forest

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**ABSTRACT**

The impact of atmospheric nitrogen (N) deposition on the soil organic carbon (SOC) pool in Moso bamboo forests is directly related to the balance and stability of the forest's carbon (C) pool. This project employs a combination of in-situ $^{13}CO_2$ pulse labeling in the field and continuous $^{13}C$ labeling in the laboratory to explore the allocation of rhizodeposited C in the soil's active organic C pool and its response to N deposition. Additionally, high-throughput sequencing and quantitative PCR techniques are used to identify key microbial functional groups involved in the degradation of rhizodeposited C and their response to N deposition. Furthermore, metabolomic analysis is conducted to investigate the effects of N deposition on key primary metabolites in the rhizosphere soil of Moso bamboo, aiming to screen for differential metabolites. The findings indicate that N deposition increases the content of rhizodeposited C (CdfR) and its allocation in SOC of the rhizosphere soil. The increase in rhizodeposited C leads to a reduction in C-degrading microorganisms and functional genes but enhances the abundance of $CO_2$-fixing microorganisms and functional genes. Model analysis reveals that the increase in the soil's active C pool is caused by the increase in rhizodeposited C, which is mainly associated with the reduction in C-degrading microorganisms and the increase in $CO_2$-fixing microorganisms. Under N deposition, C-degrading fungi in the rhizosphere soil increase while C-degrading bacteria decrease, suggesting that C-degrading fungi may preferentially utilize rhizodeposited C, leading to a decrease in $SO^{13}C$ content and an increase in the proportion of $DO^{13}C$ and $MB^{13}C$ in $SO^{13}C$. Moreover, N deposition significantly increases the content of sugars (Melibiose, D-Lactose*) and amino acids and their derivatives (L-Lysine, L-Glutamine) in the rhizosphere soil in the short term. However, as the $^{13}C$ labeling duration increases, N deposition significantly enhances the content of sugars (Sucrose-6-phosphate, D-Melezitose) and nucleotides and their derivatives (Hypoxanthine, Allopurinol). The research outcomes will provide a scientific foundation for maintaining the balance of the forest SOC pool and identifying forest soil C sinks.

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# The construction of core microbiota for phosphate-solubilizing and its regulation on phosphorus bioavailability in Moso bamboo rhizosphere

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**ABSTRACT**

The low soil phosphate (P) bioavailability is a crucial factor determining plant productivity. It is an efficient strategy to greenly improve P bioavailability for phosphate-solubilizing microorganisms (PSM) to continuously activate soil P pool. However, the single-strain inoculants are not resilient enough to provide a highly efficient and stable function in the field. The construction of synthetic microbial communities (SynComs) is expected to solve this problem through the division and cooperation between microorganisms. Moso bamboo (*Phyllostachys edulis*) forests have high productivity despite the P-limited conditions, which be attributed to the recruitment of PSM by the 'rhizome-root integrated system'. The construction of SynComs for phosphate-solubilizing and elucidating their mechanism of enhancing P bioavailability will provide new ideas for greenly improvement of soil P bioavailability and productivity of Moso bamboo forests. Coupling field sampling, laboratory culture and field inoculation tests using high-throughput isolation and screening, this study parsed out and isolated the core taxa of PSM; the stable and highly efficient core microbiota for phosphate-solubilizing can be constructed; using the soil in situ zymography, the effect of this core phosphorus-dissolving microbiota on soil P cycle and bamboo growth was explored. These results are as follows:

(1) A total of 125 P-solubilizing bacteria were isolated from the bamboo rhizosphere, predominantly belonging to the phylum Proteobacteria (96.8%), followed by Actinobacteria (1.6%) and Firmicutes (1.6%). Three strains with the strongest P-solubilizing activity against insoluble phosphorus sources, including iron phosphate, aluminum phosphate, and lecithin, were selected to construct 27 P-solubilizing bacterial communities. Among these communities, 81.0% exhibited competitive relationships (–), while 19.0% displayed synergistic relationships (+). The SynCom, composed of SI-9, SIII-4, and SIII-20, exhibited the best P solubilizing activity, particularly under low phosphorus conditions, with an activity of 66.7 $mg \cdot L^{-1}$.

(2) In low phosphorus (LP) and high phosphorus (HP) conditions, compared with the control, the SynCom inoculation decreased the soil TC/TP and TN/TP ratios, indicating soil P limitation were alleviated by SynCom inoculation. SynCom inoculation increased soil available P (AP) content, particularly in LP conditions. Under LP conditions, compared with the control and single-strain treatments, the ACP activity in the SynCom treatment increased by 186.9% and 40.9%, respectively, with the hotspot area expansion by 1.4 and 1.3 times, and the *phoC* and *phoD* gene increased by 10.0%~24.8% and 2.3%~95.0%, respectively. The contents of Free iron oxide (Fed) and Free aluminum oxide (Ald) were lower than in the control, indicating that SynCom promoted organic P mineralization by increasing soil ACP activity, expanding the hotspot area and increasing the abundance of soil microorganisms containing P-related gene. It also promoted the dissolution of secondary mineral P by reducing Fed and Ald content. In LP and HP condition, compared with the control and single-strain treatments, SynCom inoculation increased the aboveground dry weight (14.8%~128.5%) and belowground dry weight (23.2%~331.9%) of Moso bamboo. These findings lay the foundation for enhancing soil P availability and productivity in Moso bamboo forests.

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# Compartmentalized Homeostasis Drives High Bamboo Forest Productivity Under Nutrient Imbalance

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**ABSTRACT**

Stoichiometric homeostasis, the ability to maintain internal nutrient balance, is central to plant fitness under soil nutrient variability. While traditionally viewed as static, emerging theory posits it is a conditionally flexible trait, though empirical evidence is scarce. Through large-scale field investigations, nutrient additions, and data synthesis, this study shows that Moso bamboo (*Phyllostachys edulis*), a fast-growing plant species, employs a unique compartmentalized homeostasis strategy by decoupling nitrogen (N) and phosphorus (P) regulation across tissues. It achieves strict N:P homeostasis in leaves while allowing P flexibility in woody tissues to serve as reservoirs that buffer leaves from soil P limitation and microbial competition. This mechanism, consistently observed in bamboo across wide geographical and soil nutrient gradients, yields lower leaf N:P variability than 75 out of 91 co-occurring tree species, could be one of the critical factors for sustaining about 25% higher annual productivity than other forests (including evergreen-broadleaf, deciduous-broadleaf, and coniferous forest). These findings reconcile classical views of stoichiometric homeostasis and plasticity by demonstrating a flexible, compartmentalized mechanism that resolves growth-stability conflicts. Recognizing such flexible strategy advances the understanding of eco-evolutionary feedbacks in ecosystem stoichiometry and improves predictions of species adaptability, nutrient cycling, and carbon sequestration under global change.

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# Plantation conversion of Eucalyptus promotes soil microbial necromass C accumulation

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## ABSTRACT

Context: Stand conversion in subtropical regions has altered soil physicochemical properties and microbial communities, leading to changes in microbially mediated processes, such as microbial necromass C (MNC) formation and accumulation. However, previous studies on the effects of stand conversion on MNC are lacking, leading to gaps in our understanding regarding the influence of long-term stand conversion on MNC accumulation in different soil layers and the relative importance of soil properties for regulating MNC.
Aims: In this study, we used field surveys and soil analysis to assess the effects of converting a Eucalyptus forest into other planted forest (broadleaf mixed forest [BM] and Acacia mangium Acacia auriculiformis forest [AM]) on soil properties, enzyme activity, microbial community composition, and MNC after conversion 20 years in Guangdong, South China.
Results: We found that the content of soil organic C (SOC) in the surface soil (0–10 cm after litter removal) increased by 64.9% when Eucalyptus was converted to AM, whereas there was no significant difference in the subsurface soil (10–20 cm). β-1,4-glucosidase (BG) and β-1,4-N-acetaminophen glucosidase (NAG) activity increased significantly, while leucine aminopeptidase (LA) activity decreased significantly in the surface soil. In the subsurface soil, BG activity did not change significantly; nonetheless, acid phosphomonoesterase (AP) activity decreased. The fungal, bacterial, and gram-negative bacterial biomass did not significantly differ among the different forests in the surface soil, but the fungal, bacterial, gram-positive, and gram-negative bacterial biomass decreased significantly in the subsurface soil. The ratio of fungi to bacteria was highest in the BM, whereas the ratio of gram-positive to gram-negative bacteria was highest in the AM. Soil fungal and microbial necromass C and the ratio of fungal to bacterial necromass C increased significantly in the surface soil when Eucalyptus was converted to AM. The contribution of MNC and fungal necromass C to SOC content significantly increased by 22.20% and 26.23%, respectively, when Eucalyptus was converted to AM. The main controlling factors of MNC accumulation in the surface soil were pH and total N, whereas soil enzyme activity (BG related to C-acquisition) was the dominant determinant of MNC accumulation in the subsurface soil.
Conclusion: Our study confirmed that converting Eucalyptus to AM promotes MNC accumulation in the surface soil by changing soil pH and TN content to affect soil enzyme activity and microbial community structure, and ultimately changed MNC accumulation. Therefore, effective forest management practices, such as reasonable stand conversion, must be developed to enhance forest SOC accumulation by increasing MNC accumulation.

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# Afforestation improves soil multifunctionality through microbial activity and SOC molecular diversification

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**ABSTRACT**

Afforestation is widely advocated for its potential to enhance soil-based ecosystem services. However, the mechanistic understanding of how afforestation regulates soil multifunctionality (SMF)—encompassing nutrient provisioning, enzymatic activities, and microbial metabolic processes—remains incomplete. Existing research often relies on simple metrics of microbial diversity and largely overlooks the molecular diversity of soil organic carbon (SOC), an emerging dimension critical to decomposition dynamics and soil functioning.

To elucidate the effects of afforestation on SMF, we investigated a tropical restoration chronosequence comprising bare land, a *Eucalyptus exserta* monoculture, an afforested mixed-species forest, and an old-growth natural forest. We quantified SMF using averaging, multivariate, and multi-threshold approaches. Microbial community composition and functional diversity were assessed via phospholipid fatty acid analysis and GeoChip functional gene arrays, while SOC molecular diversity was characterized using analytical pyrolysis techniques.

Our results demonstrated that afforestation significantly increased SMF. This enhancement was more strongly associated with shifts in microbial community composition and increased complexity of microbial functional networks than with changes in Shannon diversity alone. Furthermore, SOC molecular diversity emerged as a key mediator linking microbial biodiversity to SMF.

By integrating microbial and SOC molecular perspectives, we believe that our findings underscore the value of promoting mixed-species plantations in tropical afforestation initiatives. They also highlight the importance of incorporating SOC molecular diversity into restoration planning to maximizing ecosystem multifunctionality.

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# Soil Carbon Sequestration in forest soils: Limits and Potential versus Potential

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**ABSTRACT**

Climate change impacts, especially warming and changes water availability have led to a general decrease in net primary production (NPP) of primary forests (Silva and Horwath 2013). Along with the effects of atmospheric $CO_2$ increases this will impact the formation and persistence of forest soil, organic carbon (SOC). Forest SOC will be impacted by changes in the quality and amounts of NPP, N availability and soil temperature and moisture. The interaction of mean annual temperature (MAT) and mean annual precipitation (MAP) has a strong influence on SOC and is a strong selector of biome type and NPP potential, which directly affects SOC levels and persistence. For example, as forest biomes are forced up elevation due to changing climate, the effect of parent material will have a strong influence on the persistence of old SOC in surface and subsurface soils with basalt and andosols showing the most stability. The quality changes in NPP inputs will be reflected in changes in the C to N ratio or other chemical changes, such as accumulation of tannins which will influence decomposer metabolic efficiency, activity, and turnover. The priming effect (PE) on SOC and or NPP inputs will change. Changes in soil MAT and MAP will affect PE in both surface and deep SOC. As roots exploration increases in response to increased evapotranspiration, the role of root exudates in SOC formation, turnover and maintenance will affect its stability through increased priming effects. The increased production and transport of dissolved organic carbon (DOC) to subsoil will destabilize mineral associated organic carbon (MAOC). These potential outcomes could occur concurrently and result in increased DOC production throughout the soil profile under rising temperature and atmospheric $CO_2$ exacerbating SOC loss. These interacting outcomes become more complicated making the prediction of SOC persistence a challenge to incorporate into biogeochemical models. The results suggest negative feedback causing increased SOC loss with increasing mean annual temperature combined with the change in the amount and frequency of MAP. While carbon storage in tree biomass is predictable, the climate and soils factors affecting the sequestration of new SOC and persistence of old SOC has been difficult to predict. SOC is an intrinsic ecosystem characteristic, and it will remain a crucial research area to ensure forest biome protection and sustainable management.

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# Forest Development Determines the Compositions and Structures of Soil Invertebrate Communities in Reclaimed Coastal Lands

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**ABSTRACT**

Soil fauna is integral to facilitating material cycles, energy flows, and the conservation of biodiversity in terrestrial ecosystems. However, the impacts of forest development on the compositions and structures of soil invertebrates remain uncertain. Here, we assessed the dynamics in abundance and diversity of soil invertebrates across eight successional age stages of *Metasequoia glyptostroboides* tree plantations (7-, 16-, 21-, 26-, 31-, 36-, 41-, 46-year-old stands) in a reclaimed coastal land in China. We used pitfall traps to collect soil invertebrates and analyzed key soil and litter properties to understand their relationships with the faunal communities. The results revealed that the total abundance of soil invertebrates initially decreased during the young to near-mature stand period (7- to 31-year-old stands), whereas it increased along the age series, from the near-mature to overmature stand period (31- to 46-year-old stands). Specifically, the dynamics showed a U-shaped curve with stand development. Further, there was a significantly negative correlation between the Shannon–Wiener diversity index and the total abundance of soil invertebrates across this plantation chronosequence. The variations in abundance of detritivores were consistent with the total abundance of soil invertebrates during stand development. The abundance and diversity of the soil invertebrates were strongly correlated with the soil environment (e.g., soil organic carbon, litter biomass, and microbial biomass nitrogen). These findings highlight that the compositions and structures of soil invertebrates were significantly altered with *M. glyptostroboides* stand development. Thus, the management of plantations should consider the abundance and diversity of soil invertebrates and functional groups for improving soil structure and fertility. This provides important insights for studying the interconnection of above- and below-ground plantation ecosystems toward their optimal management.

**Keywords:** soil invertebrates; total abundance; diversity; functional groups; stand development

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# Microbial Community Assembly, Network Resilience, and Nitrogen Functional Stability Under Canopy Gap Disturbance in Karst Forest Soils

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**ABSTRACT**

Canopy gaps are a common disturbance in subtropical karst forests, but their belowground consequences are not well understood. In particular, we know little about how gap size influences soil microbial assembly, nitrogen (N) cycling functions, and the role of rare taxa in maintaining functional resilience. We surveyed 16 natural canopy gaps (30–250 m²) in a mixed evergreen–deciduous karst forest in southwest China. Soils were sampled from the gap center, gap edge, extended edge, and adjacent closed-canopy forest. We characterized bacterial and fungal communities, built co-occurrence networks, and related community structure to soil N pools, potential N cycling processes, and indices of functional redundancy and functional stability.

Three main results emerged. (1) Canopy gaps increased both bacterial and fungal richness compared with closed-canopy soils. Bacterial richness rose steadily with increasing gap size, whereas fungal richness peaked at intermediate gap sizes. Community assembly in gaps was dominated by stochastic processes. For bacteria, the strength of stochastic assembly increased with gap size, suggesting that larger gaps promote dispersal- and drift-driven recruitment. For fungi, stochasticity followed a U-shaped pattern with gap size, consistent with stronger environmental filtering in some positions within the gap.

(2) Gap size and within-gap position reshaped microbial interaction networks. In large gaps, bacterial networks at the gap edge were more connected and more robust to simulated node loss than those at the gap center. Fungal networks showed the opposite trend, indicating contrasting stabilization strategies between bacteria and fungi. Keystone taxa in these networks were consistently drawn from rare bacterial groups rather than abundant groups. Rare taxa accounted for most network nodes, showed broader niche breadth than abundant taxa, and disproportionately maintained network robustness.

(3) Low-abundance but persistent rare taxa were the strongest biological predictors of microbial functional redundancy and functional stability, outperforming abundant taxa. Their relative abundance explained a large share of the variation in these stability metrics. Ammonium nitrogen ($NH_4^+$-N) was identified as a key environmental link between gap size and functional stability: higher $NH_4^+$-N was associated with greater microbial functional stability. Nitrogen cycling also shifted with gap size. Larger gaps tended to show higher nitrification potential, while ammonification, N fixation, and denitrification potentials tended to decline.

Overall, canopy gaps act as natural experiments that couple physical disturbance, soil nutrient status, and microbial community assembly. Our results indicate that rare bacterial taxa play a central role in holding together microbial networks, buffering N cycling, and sustaining functional redundancy in these fragile karst soils. These mechanisms suggest that managing canopy gap structure, and the associated inorganic N environment, could be used to support restoration and resilience in degraded subtropical karst forests.

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# Climate-driven shifts in microbe-mediated home field advantage in litter decomposition

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## ABSTRACT

The "Home Field Advantage" (HFA) hypothesis posits that plant litter decomposition proceeds more rapidly in situ because local soil microbiomes are functionally adapted to decompose the biochemical and structural properties of native litter inputs. However, the mechanisms driving HFA responses, and their sensitivity to climate change, remain unclear. Here, we conducted a 24-month reciprocal litter–soil transplant experiment between temperate and subtropical forests to test how litter quality, nutrient content, and microbial community composition interactively shaped HFA effects. HFA effects were observed for both litter types, but underlying mechanisms differed. Specifically, temperate litter decomposed more slowly in subtropical soils likely due to the absence of key fungal taxa (*Mortierella, Russula, Trechispora)* with ecological traits needed to degrade lower-quality litter. In contrast, high-nitrogen, low-phosphorus subtropical litter suppressed the activity of fungal decomposers in temperate soils, likely by selecting for faster-growing bacterial taxa. Decouple and recouple trends were observed based on soil transplantation to novel climates. Dominant fungal taxa progressively resembled local fungal community composition following soil transplantation, and the relative abundance of climare-specific fungal Class (e.g., *Rhizophydiomycetes*, *Dothideomycetes* and *Leotiomycetes*) was strongly correlated with temperate litter mass loss. Our findings highlight the central role of fungi in mediating HFA effects and suggest that both litter chemistry and climate-driven changes to microbial communities will shape future decomposition outcomes. As climate change alters plant species distributions and soil microbial assemblages, these interactions may become increasingly decoupled but also has recoupled trends, with significant implications for ecosystem carbon dynamics.

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# Long-term throughfall exclusion decreased soil organic carbon components by higher soil CUE and lower microbial enzyme activities on Phyllostachys edulis

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**ABSTRACT**

Soil microbial carbon use efficiency (CUE) is an important parameter in describing the assimilation efficiency of microbial organic carbon as a key indicator for measuring the potential of soil carbon sequestration. Previous studies have shown that drought can significantly affect microbial CUE, which is crucial for the carbon cycle in forest ecosystems. However, the mechanisms of microbial CUE on soil carbon stability under drought conditions are not well understood. In this study, a throughfall exclusion experiment was conducted in subtropical *Phyllostachys edulis* plantations (CK, control; T, throughfall exclusion). The results showed that drought increased microbial CUE by 9.12% ($p<0.05$) and 2.56% in 0-10 cm and 10-20 cm soil layers, respectively. Soil organic carbon (SOC), soil particulate organic carbon (POC), soluble organic carbon (DOC), and easily oxidized organic carbon (ROC) all significantly decreased, while the proportion of mineral-associated organic carbon (MAOC) in SOC increased by 4.1% and 6.3% ($p<0.05$) in the two layers, respectively. Microbial CUE was positively correlated with POC/SOC ratio and MAOC/SOC ratio, indicating that variation of SOC components substrate quality was an important factor driving microbial physiological changes. Redundancy analysis (RDA) further showed that soil polyphenol oxidase (PPO) and cellobiohydrolase (CBH) enzymes were the main factors driving changes in microbial CUE. SOC increases with microbial reproduction, CUE and turnover rate. Our results suggested that drought indirectly regulates the storage and transformation of SOC by affecting microbial community structure and function, which would have a profound impact on the carbon cycle of forest ecosystems.

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# Forest plant community and fire control on soil microbial diversity and functions related to C and N cycling and GHG fluxes

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**ABSTRACT**

The BIOSFeR[3]a project examines the relationship between species and functional diversity that drives key processes in the carbon (C) and nitrogen (N) cycles and related greenhouse gas (GHG) fluxes in natural ecosystems, focusing on the comparison of coniferous versus broadleaved forests. It also explores the differential effect of fire, on post-fire soil C and N cycling, losses, and greenhouse gas fluxes in these two plant community typologies. For this task we analyzed and compared 21 forest stands of Coniferous (Pinus nigra J.F. Arnold) and 16 forest stands of broadleaved (Fagus sylvatica L.) located in the Maiella Natural Park, in the mountain region of Abruzzo in Italy, located at about 1000 m. a.s.l. The area experienced strong fire events in 2017 and 2023. We characterized the site and sampled plant and soil samples one year after the last fire event, both in control unburned sites and in burned plots, in October 2024. Soil physical-chemical properties, chemical fingerprint, soil biodiversity, key C and N processes, 13 enzyme activities, and $CO_2$, $N_2O$ and $CH_4$ fluxes were determined. Control site data revealed a clear difference in soil microbial species coherent with the observed functional diversity, under the two plant communities, characterized by quite different chemical and microbial fingerprint, resulting in a more "open" C and N cycle in broadleaved stands compared to coniferous ones. Fire significantly and differently altered soil diversity and functions in the two plant communities, increasing post-fire C and N losses, significantly more pronounced in relative terms under coniferous cover. Data indicate that forest losses due to fire induce stronger radical changes in terms of reduction of C and N retention and GHG emission in coniferous than in broadleaved forests.

**Acknowledgments**

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# Age-related shifts in soil microbial community structure and metabolic pathways in Picea schrenkiana var. Tianschanica plantations

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**ABSTRACT**

Soil microorganisms participate in and regulate the conversion and cycling processes of soil nutrients and energy. *Picea schrenkiana* var. *Tianschanica* are the most widely distributed trees and correspond to the largest volume of tree species in the mountain forests of Xinjiang, yet the impacts of stand age on soil microbial communities remain understudied.

On the basis of information such as altitude, slope aspect, and slope position, four *Picea schrenkiana* var. *Tianschanica* plantations of different ages (30-, 40-, 50-, and 60-year-old) were selected. The soil samples collected at the same depth at each sampling point were used as nonrhizosphere soil. We analysed bacterial and fungal communities across 48 stands using high-throughput sequencing and metagenomic profiling.

The diversity of soil bacteria did not significantly differ among stands of different ages, but significant differences in community structure and species composition were detected. The structural differences were significant between the 50-year-old and 30-year-old 60-year-old plantations , and stand age explained 37% of the differences (Adonis, $P < 0.05$). The diversity index and evenness index of the soil fungal community first decreased but then increased with increasing stand age, and those of 40-year-old plantations were significantly lower than those of 50-year-old and 60-year-old plantations ($P < 0.05$) . The soil fungal community structure significantly differed between young and middle-aged forests, and stand age explained 29% of the differences (Adonis, $P < 0.05$). Mantel analysis and redundancy analysis revealed that alkali-hydrolysable nitrogen (explanation rate: 15.50%) and pH (explanation rate: 31.00%) were the main factors affecting the diversity of bacterial and fungal communities and the dominant communities at the phylum and genus levels, respectively, and soil bulk density (explanation rate: 19.90%) and alkali-hydrolysable nitrogen (explanation rate: 20.80%) were the main factors affecting the differential species and metabolic pathways of soil bacteria and fungi in *Picea schrenkiana* var. *Tianschanica* plantations, respectively.

These findings highlight the critical role of soil nitrogen dynamics in shaping microbial communities during stand development, providing insights for the sustainable management of boreal coniferous forests.

**Acknowledgments**

This research was supported by the Central Government Financial Funds for Forestry Reform and Development (Xin Cai Zi Huan [2022] No. 122) for the project "Water Source Utilization of *Picea schrenkiana* var. *Tianschanica* Forests across Different Altitudinal Gradients."

# Functional Sensitivity to Environmental Conditions Exceeds Community Composition in Forest Soils

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## ABSTRACT

Soil microbial communities are strongly shaped by tree species and environmental conditions, but it remains unclear whether shifts in microbial community composition lead to corresponding changes in microbial functions. To address this, we used multiple sampling strategies to determine whether spatial variability outweighed functional and compositional differences of soil microbial communities from beech and spruce forests. Spatial variability in composition of microbial community sampled from the same forest plot was much greater as compared with functions related to respiratory and hydrolytic enzyme activity. Much larger spatial variability was observed for enzymatic activities than for microbial respiration. Effects of spatially remote sites exceeded depth effects on microbial community composition, whereas depth had a stronger impact on enzymatic activities. Explanatory power of soil properties was stronger for variation in bacterial than fungal community composition. We demonstrated that microbial communities in forest soils are spatially distinct in composition but their functional redundancy is sufficient to maintain basic ecosystem services independently on community composition.

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# Connecting Vegetation Biodiversity and Microbial Communities Role in Carbon Cycling Dynamics along a Post-Earthquake Vegetation Natural Restoration Sequences

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## ABSTRACT

Vegetation and their interactions with soil microorganisms are central to maintaining soil organic carbon (SOC) dynamics. Yet, understanding of how vegetation diversity, microbial communities, and carbon dynamics during natural restoration in degraded mountain ecosystems remains insufficient. Our study examined five restoration phases in Beichuan County, Sichuan, located in the Longmenshan seismic belt: Y2022 (2 years), Y2020 (4 years), Y2018 (6 years), Y2013 (11 years), and Y2008 (16 years), following a widespread landslide that exposed soil leaching layers. Vegetation surveys and metagenomic sequencing were performed to identify the correlation between plant diversity, carbon cycle–related functional genes, and microbial taxa. The vegetation diversity survey reveals significant differences in temporal trends across the three vegetation types. The SOC and particulate organic carbon (POC) contents increased significantly, while mineral-associated organic carbon (MAOC) content reached its maximum in Y2013. Metagenomic analysis along the restoration gradient revealed that IC fixation and methanogenesis initially increased and then declined, whereas OC degradation exhibited the opposite trend, and methane oxidation ($CH_4$-OX) showed continuous increase. The reductive tricarboxylic acid cycle was the dominant pathway in IC fixation, and hemicellulose-degrading genes were the most abundant in OC degradation, yet their dynamics diverged during restoration. Microbial community analysis identified 391 carbon cycle–associated populations, and PCoA revealed significant differences in community structure across restoration stages, with Y2022 most divergent from other time points. Network analysis shows that module number increases initially and then decreases during restoration. From Y2022–Y2020 to Y2018–Y2013, functional modules shifted from $CH_4$-OX and IC fixation to diverse IC fixation pathways and OC degradation. By Y2008, these two processes remained central, with the Calvin-Benson-Bassham cycle becoming a stable pathway for IC fixation. Correlation analysis between vegetation and microbial diversity revealed that the three vegetation types were significantly negatively correlated with carbon–associated microbial diversity. In fact, pairwise plant–microbe relationships were predominantly positive, e.g., *Choerospondias*, *Rubus coreanus*, and *Miscanthus floridulus*. Mantel tests showed microbial and plant diversity both significantly correlated with MAOC ($P < 0.001$), the latter also significantly affected soil POC ($P < 0.001$). And dissolved organic carbon was a key environmental factor for microbes involved in IC fixation and OC degradation, along with soil TP and TK. This study elucidates the interlinkages among vegetation diversity, microbial communities, and carbon cycling during post-earthquake ecosystem recovery, providing a robust scientific foundation for guiding ecosystem restoration and soil carbon management strategies.

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# The Resilience to Climate Change and Human Activities of the Forest Ecosystems in Central Africa, South America, Southeast Asia and European Union

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**ABSTRACT**

During the past decade, the Amazon has experienced severe prolonged periods of drought (Papastefanou et al., 2022), leading to the mortality of trees and a reduction in the carbon storage of the world's largest rainforest ecosystems (Aleixo et al., 2019). The Congo Basin, the second largest rainforest ecosystem has absorbed the greatest value (-0.61Gtons) of $CO_2$ relative to the Amazon (-0.1 Gt) and the Southeast Asia, which has emitted more $CO_2$ than it had absorbed (+0.49Gt $CO_2$) in the past decade (Hubau et al., 2020). However, the greatest annual rate of net forest loss in 2010–2020, i.e., 3.9 million ha was recorded in Africa, (FAO UNEP, 2020). Congo Basin is understudied (White et al., 2021). Its future is fragile due to uncertainty of climate change and biodiversity (Beekmann et al., 2024). Natural forests are threatened, therefore, their conservation, restoration and sustainable solutions as forest plantations need to be encouraged.

Human activities as oil exploitation may affect their resilience, as shown by the potential impact of $H_2S$ emissions on soil bacterial and fungal community structure and diversity of forest plantations in the Congolese coastal plains (Koutika et al., 2020; Koutika et al., 2024). This is demonstrated by the strong positive correlation of sulphur to the prevalent bacteria *Actinobacteria* which exhibit a great ability to decompose organic residues, dominant in polluted areas (Xu et al., 2016) Conversely, the prevalence of Ascomycota fungi, negatively correlated to sulphur, withstanding environmental stresses (Egidi et al., 2019), may diminished this ability in the long term (Koutika, 2024).

Mining or oil exploitation may harm the resilience of forest ecosystems. Further investigation need to be conducted: (i) Archaea composition to further confirm the negative impact of $H_2S$ emissions, likely from oil exploitation, on forest ecosystems in Central Africa; (ii) Comparing the resilience of the forest plantations in Central Africa, South America, Southeast Asia, and European Union to human activities and climate change; (iii) raise awareness of human activities such as oil exploitation, mining on the resilience of forest ecosystems, to avoid severe and irreversible impacts on climate change, biodiversity and ecosystem services (Pascual et al., 2023).

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# Global wildfire effects on soil bacteriome and recovery trajectories

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**ABSTRACT**

Wildfires are a fundamental ecological force, now intensified by global climate change and anthropogenic activities. While their effects on macro-organisms are well-documented, the response of soil microbial communities, Earth's largest biodiversity reservoir, remains poorly understood at a global scale. Existing research is geographically constrained and has yielded conflicting results, creating critical knowledge gaps concerning the influence of factors like fire severity and soil depth, and hampering our ability to predict post-fire recovery. To address this, we synthesized a global dataset of bacterial raw sequencing data from 27 studies, encompassing over 2,100 samples from 87 locations. This study investigates how key fire characteristics (e.g., severity) and environmental context (e.g., soil horizon) mediate wildfire's effects on the structure and recovery of soil microbial communities. This global synthesis offers crucial insights into the vulnerability and resilience of belowground ecosystems, providing a scientific foundation for their management in a world increasingly prone to fire.

This global synthesis reveals that wildfires significantly reduce soil bacterial alpha diversity (Richness: -21.0%; Shannon: -9.8%) and increase community dissimilarity (8.2%). At the genus level, 36 taxa were enriched while 23 were depleted; notably, *Effusibacillus*, *Domibacillus*, and *Cohnella* exhibited massive surges (15–21-fold), whereas *UTCFX1*, *Actinomycetospora*, and *CCD24* suffered drastic declines (65–74%). These impacts are highly context-dependent: they are most pronounced in surface soils and under moderate-to-high fire severities, while subsoil horizons remain largely unaffected. Critically, we found that post-fire recovery is incomplete. Although community composition (beta diversity) tends to converge with unburned states after a decade, alpha diversity remains significantly suppressed even >10 years post-disturbance. Variance partitioning identified climate and soil pH as the dominant drivers regulating these vulnerability and recovery patterns globally.

This study offers global insights into the ecological consequences of wildfires on soil microbiomes, filling critical knowledge gaps to guide adaptive management strategies that effectively balance fire risk mitigation with the preservation of belowground biodiversity and associated ecosystem functions.

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# Identification of key bacterial taxa from native microbiome for soil monitoring after wildfire

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**ABSTRACT**

Wildfires disrupt soil structure and alter microbial diversity, reducing ecosystem resilience and delaying natural recovery. Restoring native soil microbiomes may enhance plant fitness and promote the degradation of toxic combustion by-products such as PAHs and PyOM. To identify key bacterial taxa with potential for microbiome- based remediation, we investigated wildfire-driven shifts in soil bacterial communities across a pine–oak forest in Mexico. Sixteen soil samples were collected from burned and unburned areas representing three post-fire recovery stages. Bacterial communities were characterized using 16S rRNA Illumina MiSeq sequencing and QIIME1, complemented by physicochemical analyses and culture-based isolation followed by MALDI-TOF identification.

Time since wildfire emerged as a major determinant of community composition, with significant variation along pH and elevation gradients. Burned and unburned soils differed in the relative abundance of Actinobacteria and Acidobacteria and showed enrichment of thermotolerant and pollutant-degrading taxa. Although 50% of species were shared between conditions, co-occurrence network analyses revealed higher connectivity in unburned soils, suggesting greater community stability. Pyrophilous genera such as *Massilia*, *Arthrobacter*, and *Blastococcus* were detected, with *Arthrobacter* and *Blastococcus* forming part of the core microbiome and highly connected network modules.

Culture-based analyses yielded 275 bacterial isolates, of which 126 were identified and assigned to 50 species.

Burned soils exhibited higher cultivable diversity than unburned soils. Dominant species included *Achromobacter xylosoxidans*, members of the *Enterobacter cloacae* complex, and *Bacillus cereus*. Notably, several isolated taxa were not detected by amplicon sequencing, highlighting the complementarity of cultivation-dependent and - independent approaches.

Overall, these results emphasize the value of integrating sequencing, network analysis, and culturable microbiome approaches to identify key bacterial taxa for microbiome-based restoration strategies in fire-prone ecosystems.

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# Nitrogen enrichment weakens tree diversity effects on productivity

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**ABSTRACT**

Nitrogen (N) enrichment is a pervasive environmental change known to affect the diversity and productivity of ecosystems. In grasslands, experiments have shown that the positive effect of plant diversity on productivity are robust to nutrient enrichment. Whether this result apply to forests and the underlying processes involved is unknown. Using a large-scale tree diversity experiment manipulating N addition, we quantify tree diversity effects on productivity and the impact of N addition on this relationship. Under ambient conditions, we found positive biodiversity-productivity relationship resulting from direct positive effect of tree species richness and indirect effect of tree species richness via its positive effect on symbiotic fungal richness. In contrast, N enrichment weakened the positive effect of diversity on productivity by promoting productivity in monocultures and reduced symbiotic fungal richness in mixtures. The effects of functional identity in root-fungal collaboration traits via fungal community composition on productivity were robust to N enrichment. Our results provide direct experimental evidence that N enrichment weakens biodiversity-productivity relationship in forest and underscores the importance of tree diversity and fungal communities in maintaining forest function under environmental changes.

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# MICROBIAL RECOLONIZATION DYNAMICSAND ECOLOGICAL SUCCESSION IN POST-FIRE SOILS

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## ABSTRACT

Wildfires alter the physical, chemical, and biological properties of soils, compromising fertility, structural stability, and microbial biodiversity. Recolonization of the soil microbiome is a key step in the recovery of soil functioning after fire, yet early post-fire dynamics remain poorly understood because most studies characterize ecosystems months to years after burning. Here, we collected ten soil samples from Lago Peñuelas National Reserve (Valparaíso, Chile) under two dominant vegetation types (native and exotic). Soils were subjected to a simulated fire (350 °C for 30 min) in a controlled combustion chamber, and recolonization was assessed by reintroducing microbial communities isolated from non-burned soil extracts associated with each vegetation type. We monitored microbial responses at four post-inoculation time points (1, 15, 30, and 60 days). Bacterial and fungal community shifts were characterized using 16S rRNA gene and ITS metabarcoding, respectively.

Carbon and nitrogen contents were measured by IRMS-EA, and microbiome functional activity was quantified using MicroResp™ to assess substrate-induced respiration across multiple carbon sources. We observed a clear temporal succession of the bacterial community, with increasing richness and evenness over time. On day 1, Bacillota families (e.g., Bacillaceae and Planococcaceae) predominated and community evenness was low; by day 14, Beijerinckiaceae (Alphaproteobacteria) became most prominent; on day 30, Comamonadaceae, Caulobacteraceae, and Alcaligenaceae (Pseudomonadota), together with Spirosomaceae (Bacteroidota), were enriched; and by day 60, Xanthobacteraceae (Pseudomonadota) and Isosphaeraceae (Planctomycetota) increased. In contrast, fungal evenness declined through time: Mucoromycota contributed strongly at the beginning of the assay but progressively decreased, whereas Ascomycota became dominant. Across the recolonization process, the C/N ratio decreased overall and catabolic activity declined for most substrates, suggesting that burned litter and soil organic matter provides only transient support and that new carbon inputs are required to sustain soil functioning. Overall, our results show how post-fire environmental conditions and microbiome succession jointly shape soil catabolic activity, a key process for functional soil restoration and ecosystem recovery.

Moreover, they highlight the role of source microbiota in steering post-fire successional trajectories and underscore the ecological potential of native microbial communities for restoration strategies in fire-degraded ecosystems.

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# Soil depth outweighs environmental change in shaping microbial diversity–multifunctionality relationships

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## ABSTRACT

Soil multifunctionality represents the capacity of soils to sustain multiple ecosystem processes simultaneously and is strongly regulated by soil microbial communities. However, how environmental change modifies microbial diversity–multifunctionality relationships across soil depths remains insufficiently resolved. Here, we conducted a reciprocal soil-column translocation experiment between a temperate forest and cropland in northeast China to disentangle the relative effects of environmental change and soil depth on soil multifunctionality and its microbial drivers. Soil translocation generally reduced multifunctionality, with markedly stronger declines in forest soils than in cropland soils, particularly in surface layers. In contrast, deeper soils exhibited greater functional stability, indicating a depth-dependent resistance to environmental perturbation. These declines in forest soil multifunctionality were closely associated with reductions in microbial biomass, especially bacterial biomass, following translocation. Across treatments, soil multifunctionality was more consistently associated with bacterial diversity and community composition than with fungal diversity, underscoring the dominant role of bacteria in sustaining multiple soil functions. Random forest and structural equation modeling further revealed ecosystem-specific controls on multifunctionality: forest soils were primarily regulated by soil carbon availability and moisture, whereas cropland soils were mainly constrained by soil nitrogen. These contrasting drivers reflect fundamental differences in resource limitation and nutrient cycling strategies between forest and agricultural systems. Overall, our results demonstrate that soil horizon exerts a stronger influence than soil translocation on microbial diversity–multifunctionality relationships. Forest soils are functionally more sensitive to environmental change, whereas cropland soils maintain lower but more stable multifunctionality. This study highlights the critical roles of soil depth, microbial biomass, and ecosystem-specific resource limitation in predicting soil functional responses to environmental change.

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# Effects of dead lying trunks of deciduous and coniferous trees on soil microbial communities in old-growth broadleaved forests after windthrows

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## ABSTRACT

Soil microbiota regulates biochemical processes such as the transformation and mineralization of organic matter, nitrogen fixation and carbon sequestration. Deadwood is an important element of forest ecosystems, but the impact of windthrows and deadwood on the microbial and enzyme activity, content and diversity of soil bacterial and fungal communities has been little studied. We partly filled this gap by conducting studies in Podzols, Retisols and Phaozems of old-growth broad-leaved forests (Central European Russia) in areas of mass and isolated windthrows, under fallen trunks of seven tree species and in background environments. In each of the four biotopes, soil samples were taken from the top 5 cm of horizon A under fallen tree trunks (deadwood) that were in an intermediate stage of decomposition and lay tightly on the soil surface, as well as in an area of mass windthrow without deadwood and in the background forest. Soil was collected under the trunks of *Acer platanoides, Fraxinus excelsior, Populus tremula, Tilia cordata, Ulmus glabra, Quercus robur,* and *Picea abies.* Soil physical and chemical characteristics were defined for 120 samples. Microbial characteristics included microbial biomass carbon determined by substrate-induced respiration, the rate of $CO_2$ production by microorganisms using a gas chromatograph (basal soil respiration), and the activity of four extracellular enzymes: β-1,4-glucosidase, N-acetyl-D-glucosaminidase, leucine aminopeptidase, and phosphatase, using the fluorogenic substrate method. For 63 soil samples quantitative PCR (DNA-Technology, Russia) and profiling microbial and fungal communities using 16S and ITS1-3 sequencing (Illumina, USA) were performed. Retisols differed from Podzols in texture, and thickness of horizon A, although they did not differ in bulk density and C and N content; all other chemical characteristics were lower in Podzols. Microbial and enzyme activity was higher in Retisols than in Podzols. Retisols and Phaozems did not differ in microbial and enzyme activity, but the values of physical and all chemical characteristics (such as C and N content, pH, CEC, available P and K) were significantly lower in Retisols. In loamy soils, fallen trunks reduce carbon, nitrogen, and calcium retention, as well as microbial and some enzymatic activity, but do not affect phosphorous availability and phosphatase activity. The bacterial DNA content was higher in loamy soils, while the fungal DNA content was higher in sandy soils. Under fallen trees on loamy soils, a decrease in both bacterial and fungal DNA content was observed. In sandy soils, the DNA content in samples taken under and near tree trunks did not differ, but depended on the species of fallen tree. The species diversity of fungal and bacterial communities was significant higher in loams than in sands; trunks of different tree species had different effects on the taxonomic composition of the soil microbiota under the trunks.

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# Hidden Signals After the Flames: Integrating Soil Properties and Enzyme Dynamics in a Post-Fire Landscape

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## ABSTRACT

Wildfires are major drivers of soil alteration in Mediterranean mountain ecosystems. This study presents preliminary results from control and burned plots on Monte Morrone (Majella, Abruzzo) following two wildfire events in 2017 and 2023. Soil samples were analyzed for texture, bulk density, pH, cation exchange capacity (CEC), exchangeable cations, carbon and nitrogen content, enzymatic activity, and FTIR-DRIFT spectra to assess short- and medium-term fire impacts on soil structure and function.

Soils across all plots are dominated by silty clay. Burned sites show increased sand content (14.2% in 2017 burn; 8.1% in 2023 burn vs. 7.4% in controls), suggesting post-fire sediment redistribution and erosion. Bulk density increased progressively in burned soils, reaching 1.17 g $cm^{-3}$ in the 2023 plot, reflecting compaction due to aggregate collapse and ash deposition. pH values were significantly higher in burned plots (7.80 in 2017; 7.92 in 2023 vs. 7.76 in controls), consistent with ash-derived alkaline inputs (1).

Chemical analyses indicate reductions in organic carbon and nitrogen, mirrored by decreased CEC. FTIR-DRIFT spectra reveal loss of labile organic functional groups and enrichment in aromatic, pyrogenic structures, indicating qualitative and quantitative changes in soil organic matter. Enzymatic activity declined in burned soils, particularly carbon- and nitrogen-related enzymes (glucosidases, cellulases, proteases, NAG), reflecting substrate depletion and altered soil conditions (2). Phosphorus- and sulfur-cycling enzymes also decreased, with partial recovery of some carbon-related enzymes in 2023, although activity remained below control levels.

Overall, wildfire did not drastically change soil texture but caused persistent modifications in physical structure, chemical properties, and microbial functionality. These findings highlight a post-fire ecosystem undergoing gradual biogeochemical reorganization, providing critical insights for soil recovery and management in central Apennine mountain environments.

**Acknowledgments**

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# Shifts in soil microbial resource limitation along a natural gradient of ECM tree dominance in a subtropical montane forest

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## ABSTRACT

The status of microbial resource limitation plays a central role in regulating ecosystem carbon (C) cycle. Tree mycorrhizal associations are increasingly known to regulate soil biogeochemical processes due to their differentiate nutrient acquisition strategies and litter quality, while its effects on saprotrophic microbial resource limitation remain poorly understood. In this study, we collected soil samples from 35 plots with a natural gradient of ECM tree dominance (defined as the proportion of EcM tree basal area relative to the all trees) in a subtropical mountainous forest. A full factorial C, nitrogen (N) and phosphorus (P) addition experiment were conducted to infer soil microbial resource limitation based on the responses of microbial growth. The activities of exocellular enzyme were also determined to explore the possible links between ecoenzymatic stoichiometry and microbial resource limitation. C addition induced a systematic increase of microbial growth, and C plus P addition elicited even stronger responses in all soils, suggesting that microbial growth in this subtropical forest was primarily limited by C and secondarily limited by P. With increasing EcM tree dominance, C limitation showed no significant trend, while microbial P limitation decreased. Ecoenzymatic stoichiometry indicated that microbes in this forest were mainly P limited, but this P limitation did not vary with EcM tree dominance. These results suggest that ecoenzymatic stoichiometry cannot reliably represent microbial resource limitation for growth. Variation in microbial P limitation was positively associated with leaf P content and soil N availability, but negatively associated with the proportion of labile P and the relative abundance of phosphate-solubilizing microorganisms. These findings highlight the mycorrhizal association in shaping microbial secondary P limitation, which may have implications for the maintenance of forest productivity and soil C sequestration potential.

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# Winter Dynamics of Belowground Biophysical Processes in Two Temperate Forest Soils in Wisconsin, USA

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**ABSTRACT**

Variability in snow cover regulates patterns of freeze–thaw cycle (FTC) frequency in temperate forest soils, with direct consequences for soil structure and microbial activity. By manipulating snowpack conditions, we modify FTC frequencies to quantify their effects on soil aggregate stability and microbial processes. We are implementing these experiments in northern and southern Wisconsin across two soil orders: Alfisols, characteristic of deciduous forests, and Spodosols, characteristic of coniferous forests. Our design includes forest–soil pairings that are diagnostic of one another, alongside pairings in which forest vegetation occurs on soils not typically associated with that forest type, enabling us to analyze how vegetation, soil properties, and winter climate interact to shape soil aggregation. This research aims to clarify how freeze–thaw dynamics under variable snow conditions influence soil structure and to characterize the microbial mechanisms underlying aggregation responses.

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# Impacts of Mistletoe Infection on Soil Hydrology and Chemistry in Abies and Pinus Ecosystems

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**ABSTRACT**

Mistletoe (*Viscum album*) infestation has well-documented physiological effects on host trees, yet its influence on soil processesremains insufficiently quantified. Increasing evidence indicates that parasitic plants can modify below-ground environments indirectly through alterations in canopy interception, water redistribution, and litter quality.

Our study was conducted in southeastern Poland, where mistletoe remained uncommon until approximately six years ago. Its recent and rapid proliferation in this region has introduced a new, clearly identifiable ecological factor affecting soil conditions allowing mistletoe to be examined as an emerging driver of soil hydrological and biogeochemical change. The expansion of mistletoe-bearing shoots within coniferous canopies dominated by Abies and Pinus modifies key soil-forming fluxes. Changes in throughfall chemistry, altered particulate inputs, and the presence of evergreen broadleaved biomass within a needle-dominated overstory create distinct pathways of influence on soil moisture dynamics, nutrient availability, and organic matter turnover.

This study therefore addresses a critical knowledge gap by quantifying how a newly established parasitic pressure alters soil hydrological responses and chemical properties under otherwise comparable environmental and stand-structural conditions.This study evaluates how mistletoe infection affects soil moisture dynamics and soil chemical properties within Abies and Pinus forest ecosystems. By comparing soils beneath healthy and infected trees of the same species under identical environmental conditions, we aimed to isolate the role of mistletoe as a factor influencing soil behaviour.

In Abies stands, soil moisture dynamics showed clear differences between zones. Although soils beneath infected trees maintained higher volumetric water content overall, they also exhibited significantly faster week-to-week moisture decline. This pattern indicates reduced soil moisture stability and suggests that mistletoe indirectly affects soil hydrology, especially during dry periods when infected trees appear to exacerbate moisture fluctuations. In contrast, soils beneath healthy Abies trees retained more stable moisture conditions over time. These findings highlight the sensitivity of Abies ecosystems to biotic stressors and point to mistletoe as an amplifying factor that alters short-term soil water dynamics.

Pinus ecosystems displayed a contrasting response. Soil moisture levels remained relatively stable regardless of tree health condition, reflecting both the inherent physiological resilience of Pinus species and the moderating influence of a denser ground-cover layer. This vegetation likely contributes to maintaining soil moisture while preventing strong differences between healthy and infected zones.

Soil chemical indicators including soil organic carbon, electrical conductivity, hydrolytic acidity, and cation sorption capacity showed no significant short-term differences between healthy and infected trees in either forest system. However, strong correlations among several chemical variables suggest potential pathways for long-term changes. Previous findings indicating mistletoe-driven increases in potassium and conductivity emphasize the need for continued monitoring.

Overall, the study demonstrates that the presence of mistletoe primarily affects **soil moisture dynamics**, with particularly pronounced impacts in Abies forests. Although short-term soil chemical properties appear stable, the identified relationships among soil variables indicate possible long-term implications for ecosystem nutrient balance and soil functioning.

These findings demonstrate that mistletoe should be treated as an emerging biotic driver of soil-process modification in coniferous forests, underscoring the need for its explicit inclusion in future assessments of soil hydrological functioning and nutrient cycling.

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# Subsequent Fire Alters Jack Pine Pyrogenic Organic Matter Persistence

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## ABSTRACT

Fire is a natural disturbance in many forested ecosystems around the world. Fires combust and alter existing organic matter, producing pyrogenic (or fire-affected) organic matter (PyOM), which tends to be more persistent than unburned organic matter and represents an important global carbon (C) pool. However, climate change is altering fire regimes worldwide, often increasing fire frequency and severity. How these changes will affect PyOM and subsequent C cycling remains poorly understood. In particular, what will happen to existing PyOM when subsequent fires occur?

To measure the net effects of a second fire across different depths and fire intensities, we used 2-mm-sieved unburned jack pine (*Pinus banksiana*) biomass, and jack pine PyOM pyrolyzed at 450°C and 550°C. To represent burial at different soil depths, the samples were situated at 0 cm, 1 cm, and 5 cm within an ashed and washed sand matrix, representative of the sandy soils typical of jack pine stands. High and low heat flux profiles, programmed to mirror measured data from a log burn (Luo et al., 2025), were dosed from a cone calorimeter to the sand matrix, simulating different fire intensities. We then analyzed the resulting materials for a range of properties, including tracing $CO_2$ fluxes from a 12-week microbial incubation.

We found that higher initial PyOM production temperatures, which reflect the conditions of the first fire, protected more PyOM from combustion during the second fire, across all depths and heat-flux treatments. This pattern was more evident for buried PyOM (1 cm and 5 cm) than for surface PyOM, likely due to near-complete combustion of surface materials. We also found that higher initial PyOM production temperatures led to lower mineralization following the subsequent fire.

Together, these findings indicate that heat generated from fire, location (depth) of sample, and initial PyOM production temperature all interact to affect the persistence of organic matter during and after repeated fires. These effects should be considered when evaluating the net C effects of fire on soil organic matter stocks in the context of changing fire regimes.

**Acknowledgments**

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# The decomposition and stabilization of microbial residues in forest soil

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**ABSTRACT**

Microbially-derived nitrogen (N) has been considered as one of important contributors to soil organic N, but few studies have quantified the rate of necromass N decomposition. Here, via an in situ incubation of 15N-labeled necromass, we found that ~20% of the initial 15N stabilized in the soil as non-living organic N after eight years of incubation. Bacterial, fungal, and actinobacterial necromass N showed similar decomposition pattern and mean residence time. The decomposition of microbial necromass N was best simulated by a two-pool model where a labile pool decomposed rapidly, and a more recalcitrant pool decomposed at a much slower rate. This finding contrasted with the decomposition of plant litter N, which was better simulated by a single-pool model. The stabilization of necromass N in soils after more than two years suggests the important contribution of microbial residues to soil organic N, which is most likely due to mineral protection from decomposition.

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# Icelandic old birch woodlands have valuable soil carbon reserves

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**ABSTRACT**

Mountain birch (*Betula pubescens*) is the single native woodland-forming tree species in Iceland. The woodlands are mostly found on Andisols, which are the country's main soil order. Icelandic birch woodlands have undergone a long history of severe degradation over the past millennium, reducing their cover by 90% since the human settlement approximately 1,200 years ago. Deforestation led to widespread land degradation and erosion, resulting in barren land. Today, only 1.5% is covered by native woodlands, and 45% of the land area is degraded. Therefore, the conservation and restoration of native woodlands are highly relevant and a focal point for institutions focused on land restoration, including Land and Forest, Iceland. In this study, we explored the effects of birch woodlands on soil dynamics, with emphasis on carbon reserves. We selected 10 study areas across the country with woodland chronosequences from non-forested to 60+ years old woodlands. The woodland soils are typical Andisols, with high carbon content and water retention, with allophane, ferrihydrite, and mineral-organic complexes dominating the colloidal fraction. The results demonstrated a significantly increasing trend in carbon content (%) and carbon stocks (kg/m$^2$) with increasing birch age. Old birch woodlands (+60 years old) were important soil carbon reserves at a national level, with significantly higher reserves than younger woodlands. Their high carbon values are partly explained by their andic soil properties. Dust deposition of vitric materials at 50-1,000 g/m$^2$/yr affects soil carbon dynamics, leading to a rising soil surface and, consequently, increased carbon burial. We estimated that up to 0.026 kg/m$^2$/yr of carbon is buried in areas in the vicinity of active dust sources. This is especially applicable, as birch woodlands collect near-surface atmospheric dust efficiently, increasing the carbon stocks buried in the deeper layers of birch woodland soils. Our study highlights the relevance of the carbon sinks in old woodland soils, calling for the restoration of birch on a national scale, in addition to the conservation of existing woodland soils. Restoring birch woodlands to 5% of the country (increasing their cover by 3,000 km$^2$) would lead to soil carbon sequestration equal to 7% of the country's current $CO_2$ emissions. Thus, birch woodland restoration serves as an important climate change mitigation tool.

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# Ecological Stoichiometry of Plant-Soil Systems in Pinus sylvestris var. mongolica Plantations in the Semi-Arid Region of Northeast China

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**ABSTRACT**

*Pinus sylvestris* var. *mongolica* is a keystone species in China's "Three-North" Shelterbelt Program. The nutrient balance within its plantation ecosystems is critical for regional forest sustainability. However, the spatial patterns and key drivers of carbon (C), nitrogen (N), and phosphorus (P) stoichiometry in the plant-soil system of Mongolian pine plantations across the semi-arid region of Northeast China remain poorly understood. To address this, we established ten sampling sites along a latitudinal gradient in the semi-arid Northeast. We collected leaf samples and soil samples from two depths (0–20 cm and 20–40 cm) from mid-aged plantations (approximately 15 years old). Total C, N, and P concentrations were measured, stoichiometric ratios were calculated, and their spatial patterns, interrelationships, and homeostatic characteristics were analyzed. Our findings revealed that: (1) plant leaves C, N, and P concentrations ranged 391.86–545.87 $g \cdot kg^{-1}$, 12.25–23.35 $g \cdot kg^{-1}$, and 0.72–1.87 $g \cdot kg^{-1}$, respectively, showing a unimodal pattern with increasing latitude. In contrast, plant leaves C:N, C:P, and N:P ratios (ranges: 19.24–35.39, 300.37–667.11, and 10.70–27.60, respectively) exhibited a “decrease-then-increase” trend along the same gradient. (2) Soil total carbon (TC), total nitrogen (TN), and C:N ratios generally increased with latitude, with significantly higher values in the topsoil (0–20 cm) than in the subsoil (20–40 cm). Soil total phosphorus (TP) did not show a consistent latitudinal trend. (3) Correlation analysis indicated strong positive correlations among soil C, N, and P in both layers, and between leaf N and P. Leaf C:N was negatively correlated with leaf N:P. In the topsoil, mean annual temperature was negatively correlated with soil C, N, and P, and environmental factors were closely linked to soil nutrient contents. In the subsoil, soil C:N was positively correlated with pH, while soil C:P was negatively correlated with leaf C, indicating stronger coupling between environmental factors and soil stoichiometry in this layer. (4) Homeostatic analysis showed that leaf C, C:N, and C:P shifted from homeostasis to weak homeostasis and finally to sensitive states with increasing latitude. In contrast, leaf N and P generally exhibited strict homeostasis, except for leaf P at the lowest-latitude site (Z1), which was sensitive to soil P availability. This study elucidates the spatial patterns, vertical differentiation, and environmental drivers of plant-soil stoichiometry in Mongolian pine plantations in semi-arid regions. It also highlights the nonlinear response of leaf nutrient homeostasis to latitudinal gradients, providing a scientific basis for the nutrient management and sustainable cultivation of plantation ecosystems in water-limited environments.

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# Land-use intensity restructures soil organic matter pools and stabilization pathways across forest–agriculture landscapes

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**ABSTRACT**

Understanding how soil organic matter (SOM) pools respond to land-use intensity is central to predicting carbon (C) and nutrient cycling in forested landscapes under climate change. While total soil organic carbon stocks are commonly assessed, less is known about how land-use intensification alters SOM partitioning, biological accessibility, and long-term stabilization mechanisms at landscape scales.

We conducted a broad-scale soil survey across forest–agriculture mosaics in Atlantic Canada, encompassing wetlands, mature and young forests, perennial pastures, forage-based rotations, and annual cropping systems spanning a gradient of increasing soil disturbance. At each site, soils were sampled to 30 cm depth and characterized for total SOC stocks, physically fractionated SOM pools (labile particulate, intermediate, and mineral-associated organic matter), oxidizable carbon (POX-C), microbial DNA yield, enzyme activities, soil fauna, and ancillary soil physical and chemical properties. Selected SOM fractions were further evaluated for thermal stability and radiocarbon age to assess persistence.

Total SOC stocks declined systematically with increasing land-use intensity, but this response was disproportionately driven by losses of labile and intermediate SOM fractions, while mineral-associated carbon showed greater resistance to disturbance. Forested systems maintained larger and older stabilized SOM pools, whereas intensively managed croplands exhibited younger, biologically accessible carbon with reduced thermal stability. Microbial biomass, enzyme activity, and soil fauna abundance closely tracked changes in intermediate SOM pools, highlighting strong coupling between biological communities and SOM accessibility. Spatial modeling further revealed that land-use history and disturbance intensity were among the strongest predictors of SOC distribution at the regional scale.

Our findings demonstrate that land-use intensification fundamentally reorganizes SOM pools and stabilization pathways, with implications for long-term soil carbon persistence and nutrient cycling under a warming and increasingly disturbance-prone climate. Integrating SOM fractionation and biological indicators into monitoring frameworks improves our ability to detect early degradation signals and to design land management strategies that sustain soil carbon and forest soil health.

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# Rubber-Based Agroforestry Ecosystems Enhance Soil Enzyme Activity but Exacerbate Microbial Nutrient Limitations

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**ABSTRACT**

Agroforestry ecosystems are an efficient strategy for enhancing soil nutrient conditions and sustainable agricultural development. Soil extracellular enzymes (EEAs) are important drivers of biogeochemical processes. However, changes in EEAs and chemometrics in rubber-based agroforestry systems and their mechanisms of action are still not fully understood. Distribution of EEAs, enzymatic stoichiometry, and microbial nutrient limitation characteristics of rubber plantations under seven planting patterns (RM, rubber monoculture system; AOM, Hevea brasiliensis-Alpinia oxyphylla Miq; PAR, Hevea brasiliensis-Pandanus amaryllifolius Roxb; AKH, Hevea brasiliensis-Alpinia katsumadai Hayata; CAA, Hevea brasiliensis-Coffea Arabica; CCA, Hevea brasiliensis-Cinnamomum cassia (L.) D. Don, and TCA, Hevea brasiliensis-Theobroma Cacao) were analyzed to investigate the metabolic limitations of microorganisms and to identify the primary determinants that restrict nutrient limitation. Compared with rubber monoculture systems, agroforestry ecosystems show increased carbon (C)-acquiring enzyme (EEAC), nitrogen (N)-acquiring enzyme (EEAN), and phosphorus (P)-acquiring enzyme (EEAP) activities. The ecoenzymatic stoichiometry model demonstrated that all seven plantation patterns experienced C and N limitation. Compared to the rubber monoculture system, all agroforestry systems exacerbated the microbial limitations of C and N by reducing the vector angle and increasing vector length. P limitation was not detected in any plantation pattern. In agroforestry systems, progression from herbs to shrubs to trees through intercropping results in a reduction in soil microbial nutrient constraints. This is primarily because of the accumulation of litter and root biomass in tree-based systems, which enhances the soil nutrient content (e.g., soil organic carbon, total nitrogen, total phosphorus, and ammonium nitrogen) and accessibility. Conversely, as soil depth increased, microbial nutrient limitations tended to become more pronounced. Partial least squares path modelling (PLS-PM) indicated that nutrient ratios and soil total nutrient content were the most important factors influencing microbial C limitation (−0.46 and 0.40) and N limitation (−0.30 and −0.42). This study presented novel evidence regarding the constraints and drivers of soil microbial metabolism in rubber agroforestry systems. Considering the constraints of soil nutrients and microbial metabolism, intercropping of rubber trees with arboreal species is recommended over that of herbaceous species to better suit the soil environment of rubber plantation areas on Hainan Island.

**Keywords:** enzymatic stoichiometry; microbial nutrient limitation; vector model; rubber-based agroforestry systems

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# Temperature effects on nutrient biogeochemistry along a climosequence of forest soils in South Korea

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**ABSTRACT**

Climate warming is altering biogeochemical cycles, leading to changes in soil nutrient availability. As nutrients limit the growth of plant and microbial communities, warming-induced changes will have important implications for the ecology of forest ecosystems. To assess this, we quantified soil organic matter and available nutrients along a 1700 m elevation gradient in South Korean temperate forests on Mount Baekun and Mount Jiri. The gradient represents a 10ºC change in mean annual temperature and forms a climosequence in which all soil forming factors except temperature are constrained. We sampled soils from >70 permanent forest census plots and quantified concentrations of nitrogen (N), phosphorus (P) and other essential nutrients. We predicted that (1) N availability would decline with elevation due to temperature constraints on N fixation and organic matter decomposition, and (2) P availability would increase with elevation due to weaker weathering and pedogenically younger soils. Consistent with our expectations, we find a strong shift from P deficiency at low elevation to N deficiency high elevation. Organic matter concentrations increase with elevation, indicating slower decomposition at lower temperature. Total, organic, and available forms of P increase with elevation, indicating that warmer soils are more strongly weathered and leached of P. Total N increases with elevation, but the N:organic P ratio decreases, indicating greater availability of P relative to N at lower temperature. Exchangeable cations (calcium, magnesium and potassium) and soil cation exchange capacity also increase with elevation, supporting a weaker degree of weathering in colder soils. Overall, these results indicate that climate warming will increase N availability and reduce P availability in temperate forests. This imbalance in nutrient availability has important implications for forest nutrition and ecosystem stability in a warming world.

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# Nature-based solutions for mitigating climate change: from rangelands to forests

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## ABSTRACT

Global climate change is characterized by rising temperatures and more frequent extreme weather events. Reducing anthropogenic sources of greenhouse gas (GHG) emissions and increasing carbon sequestration in terrestrial ecosystems are among the measures needed to mitigate climate change. Nature-based solutions (NbS) have become central to climate change mitigation efforts because they harness ecological processes to reduce net GHG emissions, increase carbon sequestration, and support ecosystem sustainability. This presentation will discuss the mitigation potential of NbS across rangelands, agroforests, and forested ecosystems, based on research conducted in the research group over the last decade. Proper management of grasslands, converting marginal agricultural lands to agroforests, and conserving plant diversity in forests prevent substantial carbon losses and re-establish long-term ecosystem function. Despite their high potential, the effectiveness of NbS is influenced by many factors, including soil quality, management intensity, and climate variability, underscoring the need for robust monitoring and governance frameworks to ensure the permanence of sequestered carbon and ecosystem integrity. Collectively, NbS can significantly contribute to climate change mitigation as part of a broader, multi-sectoral strategy.

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# Depth-resolved controls on phosphorus bioavailability across forest soil profiles in Northeast China

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**ABSTRACT**

Phosphorus (P) availability is a key regulator of soil microbial activity and nutrient cycling in forest ecosystems, yet the mechanisms governing its vertical heterogeneity along soil profiles remain insufficiently understood. To address this knowledge gap, we designed a depth-resolved investigation across ten forest sites spanning a broad latitudinal gradient in Northeast China. At each site, a complete soil profile was excavated from 0 to 60 cm and subdivided into six depth intervals to capture vertical variation in biogeochemical and microbial processes. This study integrates complementary measurements of phosphorus supply, mineral constraints, and microbial nutrient demand. Phosphorus bioavailability will be is quantified using diffusive gradients in thin films (DGT), together with concurrent DGT measurements of Fe, Al, and Mn to characterize mineral-associated and redox-sensitive controls on phosphorus supply. Phosphorus pool composition will be assessed using sequential Hedley fractionation to distinguish between labile, moderately labile, and residual P pools. Microbial nutrient demand and acquisition strategies will be evaluated through microbial biomass stoichiometry (MBC, MBN, MBP) and extracellular enzyme activities associated with carbon, nitrogen, and phosphorus cycling. To provide ecological context for depth-dependent functional responses, bacterial and fungal community composition will be characterized using 16S rRNA gene and ITS sequencing across soil depths. By integrating geochemical fluxes, phosphorus pool structure, microbial nutrient demand, and microbial community composition across soil profiles and sites, this experimental framework is designed to elucidate the mechanisms controlling vertical patterns of phosphorus bioavailability in forest soils and their implications for soil biogeochemical functioning.

**Keywords:** phosphorus bioavailability, soil depth gradient, microbial nutrient demand, DGT, microbial community composition

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# Deciphering the key role of core microbe in the decomposition of eucalyptus harvest residue

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## ABSTRACT

The slow natural decomposition of eucalyptus logging residues is a key constraint to the wide application of the technology for returning these residues to the forest. Microorganisms are the main participants in the decomposition process of logging residues. The development of efficient decomposing microbial resources is expected to be a breakthrough in solving the technical bottleneck of efficient reforestation with eucalyptus logging residues. This study set up a 36-month in-situ decomposition experiment of eucalyptus logging residues, analyzed the key role of core microorganisms in the decomposition of logging residues through metagenomic binning technology, and verified their role by constructing synthetic microbial communities. The results showed that the key stage of residue decomposition was 24 months, during which the microbial decomposition and transformation efficiency was the highest, and the activity of decomposition enzymes and the accumulation of microbial residue carbon (alkyl carbon, amino sugar) reached the peak. Moreover, the decomposition process followed a pattern of "bacteria dominance in the early stage - fungal drive in the later stage", and the contribution of fungi to lignin degradation significantly increased in the middle and later stages. A total of 634 high-quality metagenomic assembled genomes (MAGs) were obtained through metagenomic binning, which mainly belonged to Pseudomonadota, Actinomycetota, and Acidobacteriota. Further analysis indicated that three MAGs from the genera Puia, Conexibacter, and Afipia were the core strains for the decomposition of eucalyptus logging residues and played a key role in the process. By constructing synthetic microbial communities based on core strains and non-core strains and inoculating them into eucalyptus logging residues, the key role of core microorganisms in the decomposition of eucalyptus logging residues was verified through microcosm experiments. The results showed that the synthetic microbial community containing core strains significantly improved the decomposition efficiency of logging residues, with a weight loss rate of up to 87.73%, while the weight loss rate of the blank control (CK) was only 2.92%. This result confirmed that core strains greatly enhanced the decomposition efficiency of eucalyptus residues by regulating the synergistic effects among strains. The research results have important guiding significance for the rapid decomposition of difficult-to-decompose natural products such as straw and the maintenance of soil quality.

**Keywords:**Synthetic microbial community,core microbiome,Metagenomics Binning

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# Global-Scale Land Use Change Will Become a Huge Potential Carbon "Source" in the Future: Mechanism Analysis and Spatial Projections to 2100

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## ABSTRACT

The prediction of soil organic carbon (SOC) responses to land-use changes remains uncertain, primarily due to the inadequacy of current models in incorporating alterations in its stable microbial-derived components. Evaluating microbial necromass carbon (MNC), a crucial and persistent fraction, offers a significant opportunity to enhance the accuracy of these predictions. This study systematically quantified the differential impacts of management-driven land use change (LUC-), and ecologically restorative land-use change (LUC+) on soil carbon fractions by integrating 517 pairs of global observations using meta-analysis and spatially explicit prediction methods. Ecological restoration (LUC+) significantly boosted all carbon fractions, with microbial necromass carbon (MNC) rising by 41.45%, contributing heavily to a 30.91% increase in total soil organic carbon (SOC) and raising the MNC/SOC ratio. Fungal and bacterial necromass carbon also grew by 42.92% and 38.95%, respectively. Conversely, anthropogenic disturbance (LUC−) led to a 19.14% SOC loss but increased the MNC/SOC ratio by 10.59%. This suggests that disturbance rapidly depletes labile, plant-derived carbon, while more persistent microbial residues become a larger part of the reduced SOC pool.The meta-regression analysis reveals that soil depth, pH, and climate zone are pivotal regulatory factors, while the duration of land-use conversion (LUC_year) has significant differential impacts: it is beneficial under ecological restoration (LUC+) and detrimental under human-managed conversion (LUC-). From 2001 to 2024, global land-cover changes show that human-driven transitions (7.10 million hectares) outpaced ecological restoration (2.02 million hectares) by 3.52 times, mainly due to wetlands and shrublands converting to croplands and urban areas. A Markov chain model predicts a net loss of soil organic carbon (SOC) at 0.29 Pg C per year, totaling 22.1 Pg C by 2100. Conversely, microbial necromass carbon (MNC) is expected to increase by 1.46 Pg C per year, with bacterial necromass carbon (BNC) showing strong resilience. Tropical regions are likely to experience significant SOC loss, while mid-to-high latitude areas and regions with ecological engineering will see microbial carbon growth. This study highlights that land-use changes not only affect soil carbon quantities but also alter their chemical makeup and stability, providing essential insights for policy development.

**Keywords:** Land use change,Markov chain prediction model, Microbial necromass carbon, Carbon source, Carbon sequestration

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# Soil Organic Carbon Stocks and Controlling Factors in Planted and Natural Mangrove Forests Developed on Acid Sulfate Soils

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**ABSTRACT**

Mangrove ecosystems are among the most efficient blue carbon sinks globally, yet the mechanisms controlling soil organic carbon (SOC) accumulation remain insufficiently understood, particularly in mangrove systems developed on acid sulfate soils. This study quantified SOC stocks and their vertical distribution and identified key controlling factors using an extensive dataset collected from the Can Gio Mangrove Biosphere Reserve, southern Vietnam. A total of 98 soil profiles were sampled across planted and natural mangrove forests, with soil collected at six depth intervals (0–25, 25–50, 50–75, 75–100, 100–125, and 125–150 cm) to capture SOC dynamics throughout the soil profile. For the layer 0-150 cm, total SOC stocks ranged from approximately 579 to 893 t C $ha^{-1}$, depending on forest type. Notably, SOC stocks increased with depth, indicating that subsoil layers constitute a dominant and stable carbon reservoir in mangrove ecosystems. Planted mangrove forests stored, on average, 36% more SOC than natural forests, a difference attributed to higher root biomass production, greater root turnover, and enhanced belowground carbon inputs that promote carbon burial and stabilization in deeper soil layers.

Multivariate analyses demonstrated that soil acidity associated with acid sulfate soils was the primary factor governing SOC accumulation, likely through suppression of organic matter decomposition under strongly acidic conditions, while no significant relationships were observed between SOC stocks and salinity, tidal inundation frequency, or land subsidence. These findings provide globally relevant evidence that soil chemical constraints, rather than hydrological variability alone, play a decisive role in regulating long-term carbon storage in mangrove ecosystems, with important implications for blue carbon accounting and climate mitigation strategies worldwide.

**Key words:** Mangrove soils, Soil organic carbon, Acid sulfate soils, Vertical carbon distribution, Planted versus natural mangroves, Blue carbon

# Elevated $CO_2$ accelerates forest phosphorus cycling and alleviates fertilizer dependency

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**ABSTRACT**

The capacity of forests to sustain carbon sequestration under elevated ($eCO_2$) is theoretically constrained by the "Progressive Phosphorus Limitation" (PPL) hypothesis. Unlike nitrogen, phosphorus (P) supply relies on slow geological weathering, creating a potential bottleneck. Here, we combine a global meta-analysis with a process-based coupled model to project forest P trajectories through 2050. Contrary to PPL predictions, we find that $eCO_2$ accelerates P cycling dynamics to meet increasing demands. Specifically, $eCO_2$ drives a 21% expansion in root biomass and a 19% improvement in P use efficiency. This root proliferation triggers an 18% surge in biological P weathering (+180 Gg P $yr^{-1}$), which effectively offsets the intensified P removal from biomass harvest (+188 Gg P $yr^{-1}$). Consequently, shifts the P budget towards a surplus in most regions, reducing global anthropogenic fertilizer requirements despite higher forest productivity. These findings demonstrate that "biological mining" enables forests to uncouple carbon accumulation from external nutrient inputs, safeguarding their climate mitigation potential.

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# Optical Properties of Dissolved Organic Matter of Albic Retisols (Middle Taiga, Komi Republic, Russia)

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## ABSTRACT

Dissolved organic matter (DOM) is a significant component of soil organic matter. It plays a crucial role in forest ecosystems because DOM migration is the main factor of SOM accumulation in the subsoil and its runoff to groundwater and adjacent streams. The former is occurred by precipitation and sorption of DOM on mineral surfaces and its transformation to mineral-associated organic matter**,** the latter, on the contrary, originates from the dissolution of SOM. Thus, DOM dynamics controls carbon flows and connects the pedosphere with the hydrosphere. An investigation of optical characteristics, such as absorption and fluorescence spectra, is an easy, available and highly reproducible way to make qualitative and quantitative analyses of DOM.

Soil and adjacent streams waters were sampled in Ust-Kulom region of Komi Republic, Russia. There is a middle taiga bioclimatic zone, the study site forest is defined as the moss-covered bilberry spruce forest, the parent rock is a cover loam. According to World References Base of Soil Resources soils are classified as Albic Retisols. Water extracts from soil horizons were prepared with ultrapure water. Absorption spectra were recorded on a Shimadzu UV-1800 spectrophotometer (Japan), fluorescence ones are obtained as excitation-emission matrices using a Shimadzu Spectrofluorophotometer RF-6000. Dissolved organic carbon (DOC) content was determined by a Shimadzu TOC-L CSN analyser. Absorption and fluorescence spectra were measured in the water extracts from the fresh soil samples and water ones. Spectral data were corrected and processed by parallel factor analysis (PARAFAC). In addition, an experimental study of DOM sorption in equilibrium conditions was conducted. The parent rock from the three-meter depth was sampled, dried and sieved through 2 mm. Water extracts of soil horizons were added to the parent rock samples and shaken. Then, DOC content and optical characteristics were measured again.

PARAFAC modelling revealed that forest litter and upper mineral horizons DOM is enriched with humic- as well as protein-like components. Subsoil DOM contained more protein-like material due to precipitation and sorption of humic-like substances during DOM downwards migration, which proved by the sorption equilibrium experiment. Therefore, protein-like DOM components are more labile and recalcitrant enough to reach the subsoil of Albic Retisols and accumulate there. DOM of adjacent streams has close composition as that of albic horizons and forest litter with a big proportion of humic-like structures although they are more microbially processed. Therefore, DOM migration to adjacent streams, tentatively, comes through forest litter and albic horizons.

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# Nitrogen deposition enhances microbial carbon pump-mediated soil organic carbon formation and stabilization

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**ABSTRACT**

Although the sensitivity of litter decomposition and soil organic carbon (SOC) stocks to nitrogen deposition is well-documented, the transformation of litter into SOC and its subsequent stabilization remains poorly understood, particularly through microbial (MRC) and plant residue carbon (PRC) pathways. The response mechanisms of this process to nitrogen deposition are limited by traditional understory-based simulations that overlook canopy processes. To fill this knowledge gap, we combined an in-situ $^{13}$C-labeled litter decomposition experiment with a long-term field study comparing understory (UN) and canopy N addition (CN) in a temperate forest. We identified a bimodal pattern of litter-derived SOC formation, governed by a shift from early-stage MRC to late-stage PRC dominance. This shift facilitated sustained litter-derived mineral-associated organic carbon (MAOC) accumulation, progressively enhancing the stability of litter-derived SOC throughout decomposition. CN not only enhanced microbial carbon use efficiency by improving litter quality but also accelerated microbial turnover rate compared with UN, leading to greater litter-derived MRC formation. Similarly, CN promoted higher litter-derived PRC formation by stimulating lignin release from litter, whereas UN elevated PRC by inhibiting peroxidase-mediated lignin degradation. Litter-derived MAOC accumulation was driven solely by PRC under UN but jointly by MRC and PRC under CN, resulting in more effective enhancement of litter-derived SOC stability under CN. Our findings, for the first time, systematically elucidate the dynamics of litter-derived SOC formation and stabilization mediated by microbial carbon pump, along with their divergent response mechanisms under UN versus CN, underscoring the importance of considering canopy processes for accurately predicting forest soil carbon sequestration.

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# Contrasting effects of roots and arbuscular mycorrhizal fungi on soil carbon storage reveal divergent pathways in forest carbon cycling

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**ABSTRACT**

Roots and mycorrhizal hyphae are major pathways through which plant carbon enters soils, yet their relative roles in regulating soil carbon storage remain poorly resolved. In particular, it is unclear why enhanced microbial activity associated with belowground plant inputs can lead to either soil carbon accumulation or loss. Here, we combined a field-based ingrowth core experiment with microbial, biochemical, and biomarker measurements and a process-based carbon dynamic model to disentangle the effects of roots and mycorrhizal hyphae on soil carbon dynamics in subtropical forest stands of different ages.

After 15 months of in situ incubation, root presence led to a net increase in soil organic carbon, driven primarily by gains in mineral-associated carbon, whereas mycorrhizal hyphae resulted in a net loss of soil carbon. Roots increased microbial biomass and promoted the transfer of plant-derived carbon into microbial biomass and mineral-associated pools, while maintaining a slow but persistent recycling of mineral-associated plant-derived carbon through microbial biomass. In contrast, mycorrhizal hyphae reduced microbial biomass but enhanced extracellular enzyme activities and microbial turnover. Model-based flux analysis revealed that mycorrhizal hyphae accelerated the conversion of microbial biomass into residues while suppressing the recycling of mineral-associated plant-derived carbon through microbial biomass, thereby routing carbon toward short residence-time pathways and mineralization.

Together, our results demonstrate that the direction of soil carbon change is determined by whether microbial processing is coupled to mineral protection. Roots promote soil carbon accumulation by coupling microbial processing with mineral-associated stabilization, whereas mycorrhizal hyphae promote soil carbon loss by decoupling microbial processing from mineral recycling and stabilization. These findings provide a mechanistic framework for reconciling contrasting effects of belowground plant inputs on soil carbon storage and highlight the need to explicitly distinguish root and mycorrhizal pathways in models of ecosystem carbon–climate feedbacks.

**Key words:** mycorrhizal hyphae, SOC stabilization, mineral protection, belowground process, microbial activity

# Resilience of Mineral–Organic Carbon Interfaces Under Climate Extremes: Geochemical Controls on Soil Carbon Stability in Global Forests

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**ABSTRACT**

Soil organic carbon (SOC) stability fundamentally depends on interactions between organic matter and mineral surfaces, forming mineral–soil organic matter interfaces that act as a central hub of the global terrestrial carbon cycle. While these interfaces underpin long-term carbon sequestration in forest ecosystems, their stability under accelerating climate change and increasingly frequent extreme events remains poorly constrained. Here, we integrate a comprehensive literature synthesis with transect-based field sampling, site-level experiments, and controlled laboratory incubations to examine how acute climate changes e.g. short-term droughts and intense precipitation events alter SOC dynamics. We focus on redox-sensitive organo-mineral associations, particularly manganese-associated and iron-bound organic carbon (Mn-OC, Fe-OC) and mineral-associated organic carbon (MAOC), which are critical yet vulnerable pools. Our results demonstrate that climate extremes disrupt mineral-SOM interfaces through coupled geochemical feedbacks: drought-induced oxidation destabilizes reduced Fe-OC phases, whereas extreme rainfall promotes reductive dissolution and mobilization of Mn-OC. These processes shift carbon from mineral-protected, stable pools into more labile, microbially accessible forms, increasing the risk of soils transitioning from carbon sinks to carbon sources. By linking molecular-scale mechanisms to ecosystem-scale observations, this study provides a geochemistry-based framework for assessing SOC vulnerability under future climate scenarios. Our findings offer actionable, mechanistic insights to inform sustainable forest soil management aimed at enhancing the stability of soil carbon storage in a changing climate.

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# Reduced below-ground carbon allocation triggers contrasting nitrogen dynamics in rhizosphere and bulk soil of alpine coniferous forests on the eastern Tibetan Plateau

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**ABSTRACT**

Below-ground carbon allocation (root-derived carbon inputs) is a key mechanism regulating nutrient cycling in forest soils; however, a systematic understanding of how reductions in below-ground carbon allocation induced by global change or anthropogenic disturbances affect soil nitrogen dynamics remains limited. Here, we combined a meta-analysis across global forests with a girdling experiment conducted in alpine coniferous forests on the eastern Tibetan Plateau to elucidate the relative impacts and underlying mechanisms of reduced below-ground carbon allocation on soil nitrogen dynamics. Meta-analysis showed that overall, girdling significantly increased soil nitrate nitrogen and inorganic nitrogen contents, while reducing microbial biomass nitrogen content and fine root biomass. Field experiment results showed that girdling significantly increased inorganic nitrogen contents, net nitrogen mineralization rates, and nitrification rates in both rhizosphere and bulk soils of natural and plantation forests. However, responses in natural forests were gradual and persisted for a longer duration, whereas plantation forests exhibited rapid but short-lived responses. Girdling reduced microbial biomass nitrogen content and nitrogen availability in rhizosphere soils of both forest types, while in bulk soils it led to increased microbial nitrogen content and nitrogen availability or alleviated the early negative effects. The dominant drivers of changes in nitrogen availability differed between forest types: microbial attributes primarily regulated nitrogen availability in natural forests, whereas enzyme activities were the main explanatory factors in plantation forests. Path analysis further indicated that changes in rhizosphere soil nitrogen availability were jointly regulated by microbial properties and extracellular enzyme activities, whereas those in bulk soils were synergistically controlled by soil physicochemical properties and microbial factors. These findings suggest that reduced below-ground carbon allocation in coniferous forests of the eastern Tibetan Plateau tends to shift nitrogen cycling toward a more closed state in rhizosphere soils but a progressively more open state in bulk soils. This study highlights differential response mechanisms of soil nitrogen cycling to changes in below-ground carbon allocation across forest types and between rhizosphere and bulk soils, providing a scientific basis for predicting forest soil nitrogen cycling under global change.

**Keywords:** Meta-analysis; root-derived carbon; soil nitrogen fractions and availability; soil nitrogen cycling

# Effect of Iron Materials on Methane Emission from Paddy Field

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## ABSTRACT

Methane ($CH_4$) is one of the greenhouse gases (GHGs) emitted from paddy soil ecosystems. Together with other GHGs, such as carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$), it may induce global warming and climate change (IPCC 2001). Among anthropogenic GHGs, methane is estimated to account for 14% of the $CO_2$-equivalent emissions; rice paddy emits 60 Mt C $year^{-1}$, particularly from Monsoon Asia (IPCC 2007). When fresh organic matter is fertilized just before flooding in paddy rice cultivation, the soil becomes abnormally reduced conditions to create root-rotting, then produces $CH_4$ gas. In this study, we compared the amount of $CH_4$ gas generated and the effect of steel-making sludge and application timing and rate on $CH_4$ emission in pot experiments.

Dephosphorized slag, converter slag, and ferrous materials were used as iron-containing materials and applied to river sand and gray lowland soil (1:1). The treatments consisted of a chemical fertilizer plot, a sludge plot applied with dried sludge only, and a combined sludge-ferrous material plot. Rice was grown for 3 months. The degree of hydrogen sulfide generation, Eh transition and methane gas release were measured from the beginning of cultivation, degree of root-rot and yield and yield-components of rice were examined at harvest. We also measured the amount of ferrous in the soil after 1, 2 and 3 months of transplanting and the amount of free iron in the soil after harvest. Another pot experiment was conducted to examine application timing and application rate of slag.

The degree of hydrogen sulfide generation was enhanced in all the plots where dried sludge was applied, and there was no difference in the degree of root-rot caused by the application of each iron-containing materials. The combined use of iron-containing materials reduced methane release. Free iron and ferrous were highest in the dephosphorized slag combined plot. The amount of ferrous reached a maximum 2 months after transplanting in each slag combination plot. These results suggest that ferrous eluted from iron-containing materials can improve plant growth by dry sludge, and suppress methane release, and that dephosphorized slag is particularly effective among tested materials. When slag was applied 1 and 2 months before transplanting, $CH_4$ emission was reduced to compare with immediate application on transplanting, while more $CO_2$ was emitted from pots with slag applied 1 and 2 months before transplanting to compare with immediate application on transplanting timing. When application rate increased twice as recommended, $CH_4$ emission was reduced comparing to recommended rate, while more $CO_2$ was emitted from pots with double rate of slag application. Rice yield was not affected by application rate and timing. These results suggested that steel-making slag is feasible mitigation option to reduce $CH_4$ emission from paddy field.

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# Effects of Alternate Wetting and Drying (AWD) on Driving Factors Controlling $CH_4$ Emissions from Rice Paddy Soils

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## ABSTRACT

Alternate Wetting and Drying (AWD) is a water-saving irrigation technique increasingly adopted in rice systems as a climate-smart alternative, offering potential to reduce methane ($CH_4$) emissions. However, mitigation outcomes remain variable, suggesting that the effectiveness of AWD depends on how soil characteristics and residue management influence microbial activity and redox conditions. We hypothesize that the contrasting microbial and redox dynamics occurring during AWD cycles can lead to a hysteresis effect on net $CH_4$ emissions. This effect may depend on soil texture and residue incorporation depth, which influence redox stratification and substrate availability in the soil profile.

A mesocosm experiment was conducted using two soils of contrasting textures (coarse and fine) and two crop residue incorporation depths (shallow: 0–10 cm; deep: 20–30 cm), in a full factorial design. Following an initial continuous flooding period, two AWD cycles were implemented, progressively lowering and raising the water table in 10 cm increments. During these cycles, $CH_4$ fluxes and $\delta^{13}C\text{-}CH_4$), soil redox potential at multiple depths, and porewater chemistry (including $Fe^{2+}$, DOC, dissolved CH4, and $\delta^{13}C\text{-}CH_4$) were continuously monitored.

Preliminary results suggest a nonlinear and asymmetric $CH_4$ response to drainage and reflooding phases, consistent with a hysteresis effect. Redox potential increased during drainage, temporarily suppressing methanogenesis and partially enhancing $CH_4$ oxidation. However, emission reductions varied across treatments. Deeper straw incorporation (20–30 cm) resulted in higher $CH_4$ emissions during drainage phases when the water table dropped below –10 cm, compared to shallower incorporation. This suggests that under dry conditions, anoxic microsites at depth, enriched in labile organic carbon, can maintain active methanogenesis, while reduced water-filled pore connectivity may hinder oxygen penetration and $CH_4$ oxidation. Moreover, isotopic analyses ($\delta^{13}C\text{-}CH_4$) aim to distinguish the relative contributions of microbial and physical processes and transport mechanisms to the observed fluxes.

These findings highlight the importance of vertical interactions between redox conditions and carbon availability in determining $CH_4$ responses to AWD. While AWD shows potential for mitigation, its effectiveness may be sensitive to residue management and soil physical properties. This study contributes to a process-level understanding of $CH_4$ dynamics under AWD and informs strategies to optimize its implementation for climate mitigation in rice systems.

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# Impact of Rising Tropospheric Ozone Concentrations on Rhizospheric Carbon Pools vis-à-vis Methane Emission in Tropical Rice Soil

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**ABSTRACT**

This study employed Open Top Chambers (OTCs) to investigate the responses of $CH_4$ fluxes with respect to soil Carbon (C) pools and microbial activity in rice soil exposed to different levels of elevated ozone concentrations (e[$O_3$]). Treatments included: (i) UC = ambient [$O_3$] under open field condition (30 ± 5 ppb), (ii) CC = ambient [$O_3$] under OTC (30 ± 5 ppb), (iii) EO40 = elevated [$O_3$] under OTC (40 ± 5 ppb) and (iv) EO60 = elevated [$O_3$] under OTC (60 ± 5 ppb)]. Rice soil under EO60 conditions showed reductions of 19%, 20%, 26%, and 37% in readily mineralizable carbon, potassium permanganate-oxidizable carbon, water-soluble carbohydrate carbon, and microbial biomass carbon, respectively, over CC. The rhizospheric methanogen population declined by 12% under e[$O_3$] compared with CC. Furthermore, $CH_4$ emissions were reduced by 39% under EO60 compared to CC on a seasonal basis. This research employed path analysis using the Partial Least Squares-Path Modelling (PLS-PM) method to differentiate the factors influencing $CH_4$ emissions under varying levels of e[$O_3$]. The PLS-PM model indicated that methanogens directly affected $CH_4$ emissions, with a more pronounced effect under e[$O_3$] than CC. These insights are valuable for understanding soil-plant-microbe dynamics in an $O_3$-enriched environment, which can help reduce $CH_4$ emissions from rice under changing climatic conditions.

**Keywords:** Elevated Ozone; Methane; Open Top Chambers; Climate Change, Rice

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# Effect of dry direct-seeded and seedling-transplanted rice cultivation on methane emissions from a paddy field in Hokkaido, Japan.

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**ABSTRACT**

Rice paddies are one of the major anthropogenic sources of atmospheric methane ($CH_4$). The area of dry direct-seeded rice is increasing in Hokkaido, although puddled transplanted rice remains dominant. However, literature reporting $CH_4$ emissions from direct-seeded rice cultivation systems is extremely limited compared to that regarding transplanted rice in Japan. To evaluate the effect of different rice cultivation systems on $CH_4$ emissions, a six-year field experiment was conducted from 2017 to 2022 in a paddy field on peatland dressed with mineral soil in central Hokkaido.

In the paddy field selected for this study, transplanted rice was cultivated from 2016 to 2018 and in 2021, whereas dry direct-seeded rice was grown in 2019, 2020 and 2022. For the transplanted rice cultivation system, the field was flooded before the puddling in mid-May. Seedlings were transplanted in late May, and harvested in mid-September. For the dry direct-seeded rice cultivation system, seeds were sown into dry soil after tillage in mid-May. The field was flooded for a few days after sowing, and then drained. When the rice had grown two to four leaves, the field was flooded again and then managed in the same way as with transplanted rice cultivation. Dry direct-seeded rice was harvested in late September. Rice straw was left in the field and incorporated in the following spring in both cultivation systems. $CH_4$ fluxes were measured using a closed chamber method at three to four replications during the growing season. Groundwater levels were recorded 1.5 m below the surface.

$CH_4$ emissions during the rice growing season were 29.6±3.0,39.2±18.7, 17.5±3.8,48.9±22.6,38.3±25.0,2.6±1.5 gC $m^{-2}$ from 2017 to 2022, respectively, and showed large interannual variability regardless of the rice cultivation systems. The cumulative duration of flooding for the dry direct-seeded cultivation system was 66 – 79 days, and was shorter than that for the transplanted rice cultivation system (83 – 94 days). The flooding duration had no apparent correlation with $CH_4$ emissions. On the other hand, $CH_4$ emissions had a weak positive correlation ($r = 0.62$, $p = 0.19$) with precipitation from August 20 to September 19 of the previous year. $CH_4$ emissions also had a positive correlation ($r = 0.97$, $p < 0.01$) with the average groundwater level in September of the previous year and a positive correlation ($r = 0.91$, $p < 0.05$) with volumetric soil water content in the Ap2 horizon after the harvest in the previous year. Our results suggest that lowering the groundwater level below the Ap2 horizon and drying soil in autumn could decrease $CH_4$ emissions in the following growing season from a paddy field regardless of whether dry direct-seeded or seedling-transplanted rice cultivation is adopted.

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# The Effects of Paddy-Upland Rotation on the Six-Year Nitrogen Dynamics of $^{15}$N-labeled Cow Manure Compost

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## ABSTRACT

Cow manure is a globally abundant byproduct of livestock farming. It plays a critical role in closing the nitrogen (N) cycle in agroecosystems through its application on farmland as an N source for crops. Given that cow manure compost (CMC) has low decomposability and persists in soil over multiple cropping seasons, understanding its long-term N dynamics is essential for sustainable crop production and environmental conservation. However, most studies investigating CMC N dynamics have been limited to periods under three years in continuous paddy or upland environments. A critical knowledge gap exists regarding its behavior in a paddy-upland rotation (PUR) system, where a unique, repeated cycle of soil reduction (paddy) and oxidation (upland) may profoundly influence N dynamics. In this study, we aimed to quantitatively track the six-year N dynamics of CMC in a soybean-introduced PUR system using $^{15}$N-labeled CMC.

Microplots were established in paddy and upland fields at Kawatabi Field Center (38°74'N, 140°75'E) in a cool climate region of Japan, and were annually cultivated with rice or soybeans from 2019 to 2024. The $^{15}$N-labeled CMC was applied only in 2019, the initial year of the study period, and the annual distribution of its derived N (Ndfc) to crops and soil was investigated until 2024. Non-labeled CMC was applied annually from 2020 to 2024. The effect of annual rice-soybean PUR was evaluated in comparison with the continuous paddy (CP) treatment. We also investigated the influence of soil type, namely Fluvisol and Andosol, on the Ndfc dynamics under both management practices.

Results showed that more than 50% of Ndfc remained in the soil six years after the $^{15}$N-labeled CMC application in all treatments, with the residual ratio decreasing gradually over time. No significant differences in the residual ratio were observed among the treatments throughout the study period. Supported by its high residuality in the soil, the Ndfc uptake by crops continued throughout the six-year study period in all treatments, although the uptake ratio declined annually. In the PUR, soybeans exhibited lower Ndfc uptake, while subsequent rice showed higher Ndfc uptake compared to rice in the CP. The increase in Ndfc uptake by rice after soybean cultivation was more pronounced in the Fluvisol than in the Andosol.

In this study, we directly tracked CMC N (Ndfc) over six years, revealing that both the PUR treatment and soil types influenced the Ndfc dynamics, particularly the crop uptake. These findings suggest that the CMC application strategy should be adjusted based on the management practices and soil types. Longer-term investigations are required to accumulate observations of the effects of the PUR on the soil Ndfc residual ratio. Furthermore, physicochemical analyses of the Ndfc in the soil are also indispensable to clarify the mechanism of these long-term dynamics.

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# Utilization of Chemically Recycled Bio-based Plastic as Nitrogen Fertilizer in Paddy Soil: A Pot Culture Study for Brassica rapa

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## ABSTRACT

The global accumulation of plastic waste necessitates urgent circular economic solutions. A novel "plastic to fertilizer" technology has been developed to chemically recycle bio-based poly(isosorbide carbonate) (PIC) via ammonolysis, yielding urea as a nitrogen source and isosorbide (ISB) as a potential biostimulant (Abe et al. 2021, Agrahari et al. 2025). While previous studies confirmed the efficacy of these degradation products in artificial growth media, their performance in actual agricultural soils—particularly paddy soils, which are a major agricultural soil type globally—remains to be verified. The objective of this study was to evaluate the fertilizer effectiveness of PIC degradation products compared with commercial urea in soil culture.

We conducted a pot experiment using Fluvisol collected from the plow layer of a paddy field in Miyagi, Japan (soil texture: light clay, pH 5.2, total N: 1.86 g/kg). Komatsuna (*Brassica rapa* var. *perviridis*) was cultivated under four treatments: (1) PIC degradation products, (2) commercial urea, (3) commercial urea with ISB, and (4) a no-nitrogen control. For all N-source treatments, nitrogen was applied at a rate equivalent to 0.5 g N per pot to ensure comparable conditions.

The results demonstrated that the application of PIC degradation products significantly increased plant height, leaf number, fresh/dry biomass, and nitrogen uptake compared with the control ($P < 0.05$). Crucially, these agronomic outcomes were statistically equivalent to those obtained with commercial urea, indicating that the recycled material performed just as well as the conventional fertilizer. Although ISB was hypothesized to act as a biostimulant, no significant additional growth-promoting effects were observed in this study. This suggests that ISB may undergo rapid biodegradation by the active microbial community inherent to the paddy soil environment, preventing it from exerting long-term biostimulant.

In conclusion, this study provides the first evidence that chemically recycled PIC functions effectively as a nitrogen fertilizer in paddy soil conditions. These findings strongly support a circular economic model that repurposes plastic waste into valuable agricultural resources, offering a sustainable nutrient management pathway for crops grown in agricultural systems while mitigating plastic pollution.

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# Potential for Rapid Improvement of Low-Fertility Soils by Cattle Manure Compost Application

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## ABSTRACT

The 2011 Fukushima nuclear power plant accident caused contamination of farmland soils in the coastal areas of Fukushima Prefecture. To restore agricultural production, contaminated surface soil was removed and replaced with decomposed granite soil (masa soil), which was collected from nearby mountains and was a low-fertility sandy loam. Therefore, rapid improvement of soil productivity in these reconstructed fields is required. At the same time, effective use of cattle manure compost could help establish a crop–livestock farming system that reduces dependence on chemical fertilizers. This study aimed to evaluate the potential of cattle manure compost for improving the fertility of low-fertility masa soil.

A small-scale plot experiment was conducted continuously from 2024 to 2025 in a paddy field at the Field Science Center, Tohoku University using masa soil, and the rice plants (CV. Tsukiayaka) were cultivated there. Manure compost was applied at rates of 0, 3, 6, and 12 kg/m$^2$, with five replications. In 2024, the basal chemical fertilizer consisted of 4–10–10 g/m$^2$ (N–$P_2O_5$–$K_2O$), and transplanting was performed on May 29. Additional nitrogen fertilizer (3 kg/10a) was applied on June 25 and July 16, respectively. In 2025, the experiment continued with the repeated application of the manure compost and basal fertilizer at 6–10–10 g/m$^2$ (N–$P_2O_5$–$K_2O$) and transplanting on May 30. Nitrogen topdressing (4 g/m$^2$) was applied on July 3. Each year, soil redox potential, plant growth, yield, and the nutrient composition of plants and post-harvest soils were measured.

The results showed that cattle manure compost had both short-term and repeated application effects on rice growth and yield. In the first year, heavy compost application (6 and 12 kg/m$^2$) caused temporary growth disorders in rice. Although dry matter weight tended to increase with higher compost application rates, growth disorders resulted in similar dry weights between the 6 and 0 kg/m$^2$ plots, and larger variation was observed in the 12 kg/m$^2$ plot. The 3 kg/m$^2$ treatment showed the most balanced growth and stable dry matter accumulation. In the second year, tiller number and dry matter weight increased with higher compost rates, indicating that the negative effects of heavy compost application were temporary, and that the repeated application effects gradually improved soil fertility and rice growth.

In conclusion, cattle manure compost application improved soil fertility and crop productivity over time, although heavy application temporarily suppressed rice growth. Based on these findings, two management strategies are proposed: (1) Moderate compost application (3 kg/m$^2$) is recommended to maintain stable rice growth and minimize the risk of early growth disorders; and (2) Heavy compost application (12 kg/m$^2$) may be an alternative for long-term soil fertility improvement, despite its short-term negative effects. Continuous monitoring of soil chemical and biological properties is required to clarify the long-term sustainability of compost use in paddy fields.

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# Persistence and controls of soil organic carbon in paddy fields across Asian countries: a soil physicochemical fractionation approach

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**ABSTRACT**

Soil organic matter in paddy fields plays important roles such as maintenance of soil fertility for rice production and mitigation of or adaptation to global warming through soil C sequestration. To better understand the situation in Asia, this study aimed to evaluate the amounts and persistence of SOC in multiple fractions and to elucidate their determining factors using the total of 253 paddy soils across 7 Asian countries under different climatic and geological conditions. SOC was fractionated into four fractions based on their physicochemical properties: (1) coarse light fraction (LF) derived from plant residue, (2) coarse heavy fraction (HF) containing stable aggregates, (3) fine NaClO oxidizable fraction (OxF), and (4) fine NaClO non-oxidizable fraction (NOxF) associated with fine-textured minerals. The C content of each fraction was determined by dry combustion method and $\Delta^{14}C$ values were measured to infer SOC turnover time. The relationships between the amounts of fractionated SOC and soil- and climate-factors were investigated.

The total C content was on average 22.5 gC/kg and ranged in the order of Japan (29.6 gC/kg, n = 73) > Malaysia (27.8, 40) > Philippines (18.5, 37) > Taiwan (18.2, 30) > Thailand (18.2, 16) > South Korea (16.5, 25) > Nepal (15.1, 32). The averages and percentages of fractionated C for all the samples were OxF (8.9 gC/kg, 43 %) > NOxF (6.9, 33) > LF (3.3, 16) > HF (1.9, 9), indicating that dominance of fine-grain fractions in soil C storage. The average $\Delta^{14}C$ values of selected samples were OxF (8 ‰) > HF (-54 ‰) > NOxF (-169 ‰), suggesting slow turnover of oxidation-resistant C. Total C and C contents in OxF and NOxF correlated positively with pyrophosphate-extractable Al and Fe (Alp, Fep), oxalate-extractable Al and Fe (Alo, Feo) and clay content ($p<0.01$) and negatively with pH and mean annual temperature ($p < 0.01$), indicating strong influence of soil organo-metal complexes and short-range order minerals (reflecting volcanic activities) and soil pH, in addition to temperature. Exchangeable Mg and Ca correlated positively with C content in HF, implying their influence on aggregate formation. Multiple-regression analysis further revealed that roughly 47 and 66% of the C variations in OxF and NOxF were explained by the above variables for all the samples, suggesting stronger control on the stable fraction. Furthermore, the major controlling factors for OxF and NOxF varied across pH ranges: (1) Fep and Alp for pH 4.6–5.5, (2) Alo–Alp, Alp, and Fep for pH 5.5–7.5, and (3) exchangeable Mg and Feo–Fep for pH 7.5–8.4, suggesting distinct mechanisms depending on soil pH. These findings help to better manage SOC levels in paddy fields to achieve sustainable rice production and environmental conservation.

**Keywords:** Asia, fractionation, paddy soils, radiocarbon dating, soil organic carbon (SOC)

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# Decades of intensive rice cropping alter tropical soil fertility

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**ABSTRACT**

Sustaining soil fertility under continuous intensive rice cultivation remains a major challenge in tropical Asia, where rice demand continues to increase and year-round cropping systems are expanding. Although triple rice cropping is practiced in several tropical regions, long-term empirical evidence on the effects of decades of intensive cultivation and fertilization on soil properties remains limited. This knowledge gap constrains the development of nutrient management strategies that sustain high productivity while preventing soil degradation. The present study analyzes multi-decadal trends in soil fertility under varying nitrogen (N) fertilizer inputs in a tropical paddy field, using data from the world's longest-running long-term continuous cropping experiment (LTCCE) at the International Rice Research Institute (IRRI) in Los Baños, Philippines. Established in 1962, the LTCCE features triple rice cropping with contrasting N fertilizer treatments. Since 1999, four N treatments (N1–N4: 0, 155, 310, 465 kg N $ha^{-1}$ $year^{-1}$) have been maintained while phosphorus (110 kg $P_2O_5$ $ha^{-1}$ $year^{-1}$) and potassium (70 kg $K_2O$ $ha^{-1}$ $year^{-1}$) were applied uniformly across treatments. Aboveground residues were removed after each harvest. Soil samples were collected from 0–15 cm depth in 1985, 1995, 2005, 2015, and 2019 were analyzed for total carbon (TC), total nitrogen (TN), available nitrogen (AN), available phosphorus (AP), and exchangeable potassium (Ex-K).

TC and TN increased steadily across all treatments, including the unfertilized N1 plot, with higher values generally observed under greater N inputs. In contrast, AN and Ex-K declined over time in all treatments. AN was positively correlated with N input, whereas Ex-K was the highest in the unfertilized N1 plot and the lowest under high-N inputs. AP increased across all treatments until 2005, but subsequently plateaued or declined, particularly under the N4 treatment. The AP accumulation rate between 1985 and 2005 was greatest in N1.

The concurrent increases in TC and TN, even without N fertilization, suggest contributions from belowground biomass and biological N inputs through *Azolla* and N-fixing microbes under triple rice cropping. However, the decline in AN despite rising TN indicates a shift toward more recalcitrant organic matter and reduced N mineralization under intensified rice cultivation, consistent with previous findings (Cassman et al., 1995; Olk et al., 1996). Lower N inputs resulted in higher soil P and K accumulation, likely due to lower plant uptake and export in low-N treatments.

Overall, triple rice cropping can enhance stable soil organic carbon stocks even with residue removal, but it concurrently reduces soil N supply capacity, increasing dependence on external N inputs. The observed imbalance between N, P, and K dynamics highlights the need for site-specific nutrient management guided by regular soil testing and strategies to optimize nutrient cycling in intensifying tropical rice systems.

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# Higher Efficiency of Nano-Sized Lime for Improved Limestone Conservation

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## ABSTRACT

In Malaysia, paddy is the second largest agricultural land-use after oil palm which covers 647,936 hectares, with most of the soils are acidic. Malaysian paddy farmers rely heavily on government-subsidized program of using ground magnesium limestone (GML) at a rate of 3 tons per hectare for every 3 years. This standard practice of liming, without accounting for the varying acidity levels of different fields, does not address specific soil needs and is therefore unsustainable environmentally. Furthermore, overreliance on GML, a finite resource, raises concerns about long-term availability and unnecessary greenhouse gas emission. Understanding the efficacy of liming materials in increasing the pH of different soil types is essential to address timely pH adjustment for crop requirement. This study evaluates the effects of fine (2 µm) liquid lime (CaCO3) versus l00-mesh (149 µm) GML (CaMg(CO3)2) on soil pH, exchangeable acidity, cation availability, and $CO_2$ emissions, providing insights into their efficiency and environmental impact. Soil samples were collected from major paddy granary areas across Peninsular Malaysia, including Perak, Pahang, and Kedah. These samples were air-dried and sieved through a 2 mm mesh. The soils were incubated at field capacity with equivalent carbonate doses and sampled for pH (1:2.5), $CO_2$ emission and exchangeable acidity at different intervals for 372 days. Meanwhile, exchangeable cations $Ca^{2+}$ and $Mg^{2+}$ in the incubated soils were also sampled. Results show that liquid lime, characterized by its finer particle size compared to GML, exhibited a more rapid reaction in all soil types. Liquid lime achieved a higher increase in soil pH in the early stages of treatment, which stabilized at a plateau throughout the incubation period without any crossover between treatment profiles. In addition, liquid lime markedly reduced both hydrogen ($H^+$) and aluminum ($Al3^+$) exchangeable acidity at a faster rate than GML. After three months, the reduction in $H^+$ concentration in GML-treated soil was similar to that of liquid lime. Furthermore, soils treated with liquid lime demonstrated higher available calcium ($Ca2^+$) levels, an important indicator that the finer particle size contributes to a larger reactive surface area, which subsequently improves the release rate of $Ca2^+$. On the environmental side, although liquid lime was more efficient in acid neutralization, GML treatments consistently produced higher $CO_2$ emissions. In conclusion, liquid lime demonstrated greater efficiency, achieving a rapid pH increase and acidity reduction in the early stages of incubation, making it particularly suitable for urgent soil remediation.

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# Dry direct seeding rice and water saving irrigation reduce root exudation of organic acids and methane emission from paddy soils

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## ABSTRACT

**Introduction:** Paddy rice is a staple food for > 50% of global population, while paddy soils are substantial (> 10%) sources of methane ($CH_4$) emitted anthropogenically. Water saving irrigation is expected to reduce $CH_4$ emission, but water drainage promotes aerobic decomposition and increases risk of soil degradation. Alternative wet dry irrigation management can reduce ca. 55% of methane emission (Minamikawa et al., 2025), while water saving irrigation and dry direct-seeded rice (DDSR) are assumed to decrease $CH_4$ emission by ca. 80%, with increasing emission risks of nitrous oxide ($N_2O$) and carbon dioxide ($CO_2$) from aerobic decomposition of soil organic matter. However, overall impacts of water management on greenhouse gas emission are variable between soil types and climates. Especially, water management practices could affect root exudation of organic acids, the potential substrates for methanogenesis. We tested whether DDSR and water saving irrigation change greenhouse gas emission, root exudation, and soil microbial composition, compared to continuous flooding.

**Materials & Methods:** We compared three water management practices [continuous flooding (CF), water saving irrigation (WS), and dry cultivation (DC)] of the paddy rice systems in Tottori, Fukushima, and Akita prefectures in Japan. The fluxes of greenhouse gas emission ($CO_2$, $N_2O$, and $CH_4$) were periodically measured using the closed chamber method in each plot. Greenhouse gas emission trade-off between $N_2O$ and $CH_4$ were assessed using global warming potential values relative to $CO_2$ [27 ($CH_4$) and 273 ($N_2O$); IPCC]. Mature rice roots were rinsed with distilled water to remove soils and grown in hydroponic systems to collect root exudates. Root surface areas were measured with WinRhizo. Organic acids in root exudates were measured by high performance liquid chromatography. Soil pH, bulk density, soil C and N concentrations, microbial biomass C and N were measured. Prokaryote (bacteria and archaea) and fungal community diversities in soils were assessed. Prokaryote rRNA 16S (V4 region) gene was amplified and fungal rRNA Internal Transcribed Spacer 1 (ITS1) gene was amplified with PCR to compare microbial diversity and relative abundance of methanogenic archaea.

**Results & Discussion:** Soil pH was lower in the DC plot, compared to CF and WS plots. Soil bulk density decreased by dry cultivation without puddling. The $CH_4$ emission fluxes follows the order: CF > WS > DC, while the higher fluxes of $N_2O$ emission were observed in the WS and DC plots, compared to CF plots. However, overall impacts on global warming potentials were still smaller in the DC and WS plots, compared to the CF plot, suggesting a decrease in global warming potentials by water saving irrigation and dry cultivation. Major organic acids released from roots were acetate, followed by malate and citrate. Root exudation rates of acetate, the substrates for methanogenesis, were greater in the CF plot than in the DC and WS plots. The fungal diversity was lower in the CF plot than in the DC and WS plots. The relative abundance of methanogenic archaea was also higher in the rice root of the CF plot, compared to the DC and WS plots. The relative abundance of methanogenic archaea was also higher in the rice root of the CF plot, compared to the DC and WS plots. Despite there being tradeoff between reducing greenhouse gas emission and increasing rice yields, increasing management options for farmers can provide opportunity to get C credit without increasing labor costs at the expense of crop yield.

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# Dual Benefits of Nano-Iron Oxide: Enhancing Rice Yield and Mitigating Greenhouse Gas Emissions Across Diverse Paddy Soils

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## ABSTRACT

The application of nanotechnology in agriculture offers a promising strategy for achieving sustainable intensification, yet the efficacy and mechanisms of nano-fertilizers like iron oxide nanoparticles (FeONPs) across varied soil environments remain inadequately explored. This study investigated the dual effects of FeONPs on rice productivity and greenhouse gas (GHG) emissions in three major paddy soils of China: black soil, red soil, and hydragric anthrosol. A two-year pot experiment was conducted with two FeONPs application rates (10 mg·kg$^{-1}$, T1; 100 mg·kg$^{-1}$, T2) applied as basal fertilizer, compared to a traditional fertilization control.

Regarding yield and plant physiology, FeONPs demonstrated significant benefits. The T1 rate (10 mg·kg$^{-1}$) was identified as optimal for yield enhancement. It significantly increased grain yield by up to 61.69% and 74.85% in hydragric anthrosol over two years, and showed a consistent increasing trend (34.93-46.43%) in red soil. This yield improvement was attributed to enhanced photosynthetic performance from the booting to mid-grain-filling stages. Consequently, key yield components such as spikelet number per panicle, seed-setting rate (increased by up to 53.03%), and 1000-grain weight (increased by up to 8.92%) were synergistically elevated.

FeONPs exhibited a strong capacity for mitigating methane ($CH_4$) emissions. The higher application rate (T2, 100 mg·kg$^{-1}$) was more effective, achieving $CH_4$ emission reductions ranging from 24.39% to 60.92% across soils. This suppression was mechanistically linked to an increased abundance of methanotrophic bacteria and a concurrent decrease in dissolved organic carbon availability. Furthermore, FeONPs application, particularly T2, increased soil organic carbon content by up to 4.96%, indicating a potential for soil carbon sequestration.

The impact on nitrous oxide ($N_2O$) emissions was soil- and rate-dependent. While the lower rate (T1) had minor or variable effects, the higher rate (T2) consistently and substantially reduced $N_2O$ emissions by 43.81% to 59.85% in black soil and hydragric anthrosol. The underlying mechanisms were soil-specific. In acidic red soil, FeONPs likely modulated the ammonia oxidation process by influencing ammonia-oxidizing archaea (AOA). In alkaline soils (black soil and hydragric anthrosol), the reduction was associated with the inhibition of ammonia-oxidizing bacteria (AOB) and the promotion of complete denitrification.

In conclusion, FeONPs present a viable nano-enabled strategy for synergistically enhancing rice production and reducing GHG emissions, primarily $CH_4$ and $N_2O$. The effects are mediated through the improvement of plant physiological processes and the regulation of key soil microbial communities involved in carbon and nitrogen cycling. For optimal outcomes, application rates should be tailored to specific goals: the 10 mg·kg$^{-1}$ rate is recommended for maximizing yield, whereas the 100 mg·kg$^{-1}$ rate is more effective for GHG mitigation. This study provides critical insights for the precise and soil-specific application of FeONPs to support climate-smart rice cultivation.

Keywords: Rice, Yield, Greenhouse Gas, nano-fertilizers

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# Feasibility of Pot-Grown Seedling Transplanting as an Alternative Strategy to Mitigate CH4 Emissions and Enhance Rice Productivity in a Paddy Field

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## ABSTRACT

Rice (*Oryza sativa* L.) cultivation is a major source of methane ($CH_4$) emissions, requiring effective mitigation strategies. Pot-grown seedlings (pot seedlings) may reduce $CH_4$ emissions by enhancing early root establishment and oxidation activity at the initial stage of rice growing, thereby increasing $CH_4$ oxidation; however, it remains unclear. A field experiment was conducted to evaluate the effect of seedling tray type on mitigating $CH_4$ emission during rice cultivation. An early-maturing (*Jomyeong 1*) and late maturing cultivar (*Shindongjin*) were selected, and both bed seedlings (conventional seedlings as control) and pot seedlings were prepared. $CH_4$ emissions were monitored during the seed bed preparation stage and the whole rice cultivation period using the closed chamber method. In addition, rice growth characteristics, grain yield, and yield-scaled $CH_4$ emissions were investigated during the cultivation period. Furthermore, an incubation experiment was conducted to determine $CH_4$ oxidation potentials in soils and roots at major rice growth stages. Our results showed $CH_4$ emissions were negligible during the seedling tray stage for both conventional seedlings and pot seedlings. During the whole rice cultivation, pot seedling treatments effectively decreased $CH_4$ emissions by 36% and 9% (early and late maturing varieties, respectively) compared to the control, indicating effective reduction on $CH_4$ emissions. Regardless of cultivar, grain yield showed higher in the pot seedling treatments than in the controls, which might be associated with increased the number of grains per panicle and improved the ripening ratio. Yield-scaled $CH_4$ emissions were reduced under pot seedling treatments, showing reductions of 8-47% relative to the control, indicating a better sustainable option. Overall, biomass productivity at the initial stage of rice growing significantly increased by 78% and 40%, at the early-maturing and late maturing cultivar, respectively compared to the control, indicating better growth conditions. Our study revealed a negative correlation between the number of grains per panicle and $CH_4$ emissions, suggesting that greater carbon allocation to grain formation may reduce substrate availability for methanogenesis, thereby lowering $CH_4$ emissions. In the incubations, root oxidation potential was higher than the control. Overall, transplanting pot seedlings promoted early root growth in rice, which likely enhanced root activity and increased $CH_4$ oxidation potential, thereby reducing overall $CH_4$ emissions. Therefore, pot seedling transplanting could be a promising strategy for mitigating $CH_4$ emissions while maintaining grain productivity in rice cultivation.

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# Transplanting Date Potentially Modulates Post-Season Methane Emissions via Residual Root Carbon Inputs in a Mono-Rice Paddy Field

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**ABSTRACT**

Adjucting rice transplanting date is one of the main factors substantially influencing rice growth and biomass prodction by altering meteorological conditions and flooding duration, thereby significantly affecting methane ($CH_4$) emissions in rice paddy ecosystems. Residual root biomass can serve as a potential carbon (C) source for anaerobic decomposition in flooded paddy soils and may stimulate $CH_4$ emissions in the post rice cropping periods. However, the effects of shifting transplanting dates on the quantity and quality of root biomass, and the consequences for $CH_4$ emissions during the following season, remain unclear. A field study was carried out over the three years (2022–2024), in which two rice cultivars (late and early maturing) were transplanted on four dates: May 10 (Time1), May 25 (Time2, locally recommended date), June 9 (Time3), and June 24 (Time4). $CH_4$ emissions, rice growth and psysiological characteristics were monitored throughout the rice cropping seasons. At harvest, root biomass was quantified and its chemical characteristics, including C, N content, and C/N ratio were analyed to evaluate their potential contributions to $CH_4$ emissions in the subsequent rice cultivation season. Regardless of cultivar, cumulative $CH_4$ emissions peaked at Time1, and significantly decreased by 24–87% with delaying transplanting dates in rice cropping season over the earliest date as decreased flooding duration during rice cultivation and rice growth that minimize plant-mediated $CH_4$ transport. Interestingly, mean daily $CH_4$ fluxes were also decreased significantly with delaed transplanting, consistent with the observed reductions in cumulative $CH_4$ emissions despite a shorter flooding duration. These results imply a potential shift in methanogenic activity and intensity, which may be associated with altered soil C availability influenced by residual root-derived C in paddy soils. Regardless of cultivar and investigation year, root biomass at harvest significantly decreased with delayed transplanting, accompanied by changes in C and N composition. Notably, the potential C input from residual roots showed a strong positive correlation with $CH_4$ emissions during the following season, indicating that residual root-derived C in soils could be potential methanogenic substrates, which substantially influence post-season methanogenesis and stimulate $CH_4$ emissions. Our findings suggest the quantity and quality of residual root biomass remaining after harvest should be newly considered one of the key parameters, potentially influencing $CH_4$ emissions during the following cropping seasons in a mono-rice paddy system.

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# Feeding the world while mitigating climate change: a global meta-synthesis of agronomic pathways for low-emission rice

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**ABSTRACT**

Rice sustains half the global population, yet its cultivation is a major source of greenhouse gas (GHG) emissions. Meeting rising demand calls for agronomic interventions that increase yields while curbing GHG emissions. Here, for the first time, we conducted a meta-synthesis of 91 meta-analyses to quantify the effects of 54 rice agronomic interventions, grouped into 14 categories, on yield, $CH_4$ and $N_2O$ emissions, global warming potential (GWP), and GHG emission intensity (GHGI). Biochar consistently delivered co-benefits, increasing yield by 12%, and reducing $CH_4$, $N_2O$, and GHGI by 15-18%. In contrast, residue incorporation and organic amendment raised yields (5% and 19%), but sharply increased CH4 emissions (144% and 76%) and GWP (96% and 65%). No-till or reduced tillage lowered GWP by 15% without a yield penalty. Water-saving technologies cut $CH_4$ emissions by 50% and GHGI by 39%, with a slight yield decline (-3%). Within this category, intermittent irrigation offered the best balance, while non-flooded systems achieved greater emission reductions but incurred larger yield losses (-9%). Inorganic nitrogen fertilizer increased yields by 31% but raised $N_2O$ emissions by 130%. Innovations, including deep placement and enhanced-efficiency fertilizers, reduced $N_2O$ emissions by up to 38% and improved yields by 6%–19%. Symbiotic systems (e.g., rice–duck) reduced $CH_4$, though effects on $N_2O$ were variable. While several agronomic interventions show promise, evidence remains limited for others (e.g., liming, crop establishment, weed management). Assessment of integrated approaches is needed to elucidate synergies and trade-offs, enabling the design of scalable, sustainable rice systems tailored to diverse contexts.

**Acknowledgments**

This work was supported by the Government of Japan through the project "Development of Rice Cropping Systems Toward Carbon Neutrality and Food Security in ASEAN Countries," implemented at IRRI.

# Evaluating Rice Ratoon as a Novel Carbon Source and Identifying Growth-Regulating Factors in Mono-Rice Paddies in a Monsoon Region

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**ABSTRACT**

Incorporation of organic amendments, such as rice straw, has been recommended to enhance soil organic carbon (C) sequestration and maintain soil quality in rice paddies. However, rice straw is largely removed from fields for uses such as animal feed, reducing organic C inputs to rice cropping systems. Therefore, alternative organic input sources are required. In this study, the ratoon of rice (newly emerged shoot and root biomass as green biomass), and without ratoon rice as the control where investigated at three sampling locations after rice were harvested in the field (n=168). The chemical properties of the ratoon biomass such as total and dissolved C, nitrogen, moisture content, and the characteristic of decomposition rate were determined by an incubation experiment after ratoon rice were added in paddy soils. Moreover, soil properties such as soil moisture, pH, available nutrients etc. sampled from the fields were investigated to estimate growth-regulating factors for new ratoon biomass. Our results revealed that newly-grown rice ratoon biomass could have a strong potential for enhancing soil organic C in rice paddies. Moreover, C input was significantly increased mainly due to increased shoot biomass input, indicating the promising potential for enhancing soil C. Chemical properties of the newly grown-ratoon biomass were differed at the different sampling locations. The green biomass significantly increased overall soil C accumulations, which assumed approximately 2.3 to 5.8 Mg d.w $ha^{-1}$ (334 kg C $ha^{-1}$ $yr^{-1}$). To identify the key factors triggering rice ratoon growth, soil moisture content was one of the main parameters in this study, showing strong positive correlation ($r=0.412$, $p<0.001$). Conclusively, the newly-grown ratooon biomass could be a potential carbon source in rice paddy ecosystem. However, rational cultivation management strategies should be developed rational soil water and fertilization regimes to maximize soil C sequestration potential by enhancing rice ratoon biomass in paddy ecosystems.

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# Alternate Irrigation Reduces Methane Emissions in Malaysian Rice Paddies

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**ABSTRACT**

Continuous flooding (CF) in Malaysian rice paddies under anaerobic soil conditions results in elevated methane ($CH_4$) emissions. Alternate wetting and drying (AWD) and mid-season drainage (MD) introduce periodic soil aeration, which can restructure soil microbial communities and modify methane ($CH_4$) fluxes. A tank experiment using Briah series *(Fine, mixed, isohyperthermic, Typic Endoaquepts)* soil planted with the MR297 rice variety was conducted to compare CF, AWD, and MD treatments arranged in a randomized complete block design. Methane fluxes were measured weekly using non-flow-through static chambers and gas chromatography, and interpolated weekly mean fluxes were used to estimate cumulative seasonal $CH_4$ emissions. Soil samples from the 0–15 cm layer were collected at 58 and 96 days after transplanting for 16S rRNA amplicon sequencing, and microbial community structure was assessed using Bray–Curtis principal coordinates analysis (PCoA), heatmaps of the 50 most abundant genera, and LEfSe biomarker analysis in MicrobiomeAnalyst. Seasonal cumulative methane emissions were 70.24, 30.75, and 15.93 g $CH_4$ $m^{-2}$ under CF, AWD, and MD, respectively, corresponding to methane reductions of 56.21% under AWD and 77.32% under MD relative to CF. Plant height, leaf area, and grain yield did not differ significantly among irrigation treatments, indicating that AWD and MD imposed no yield penalty. PCoA revealed significant separation of microbial communities among treatments at both 58 and 96 days after transplanting (ANOSIM, $P = 0.001$), with CF communities clearly distinct from AWD and MD at 58 days, and AWD showing the most significant divergence at 96 days. Soils under CF were enriched in hydrogenotrophic methanogens, particularly Methanocella (Rice Cluster I) and Methanobacterium (Euryarchaeota), which coincided with higher methane emissions. In contrast, AWD and MD soils exhibited higher relative abundances of methanotrophic taxa such as Methylocystis (Alphaproteobacteria) and Pseudomonas (Gammaproteobacteria), consistent with enhanced methane oxidation and lower net $CH_4$ emissions. Alternate wetting and drying and mid-season drainage substantially reduced methane emissions from Malaysian paddy soil by approximately 77%, while maintaining rice physiological performance and yield. These mitigation effects are closely linked to a functional shift from methanogen-dominated microbial communities under continuous flooding to methanotroph-enriched assemblages under alternate irrigation regimes. Overall, the findings demonstrate that water management practices that steer soil microbial abundance and diversity provide a viable strategy for reducing paddy methane emissions without compromising productivity.

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# Soil carbon budgets under three different fertilizer management in paddy fields, Japan.

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## ABSTRACT

Application of organic matter is increasingly important for soil amendment or resource circulation, while the supply of organic substrates such as cow manure and rice straw residue risks increasing the emission of methane ($CH_4$) and carbon dioxide ($CO_2$) from paddy soils. Despite the potential risk, organic matter application to the paddy fields has the potential to increase soil carbon stocks under flooding conditions. This C input is hypothesized to be greater than C output in Andisols because of their high capacity to store organic matter. To test this, we measured microbial organic matter decomposition rates and calculated soil C budgets in an Andisol paddy soil under different fertilizer and manure management.

We compared three treatments (manure, chemical fertilizer, and no fertilizer application) in Andisol paddy fields at Experimental Farm of Utsunomiya University. Manure application has continued over 44 years. Soil C concentrations after 44 years application were determined by NC analyzer. Gas fluxes and drainage were measured as C output from paddy soils, while rice straw residue, manure, weed biomass were measured as C input to calculate soil C budgets. Gas samples were periodically collected using the closed chamber method to determine $CH_4$ and $CO_2$ fluxes in each plot. The loss of dissolved C through drainage was estimated by measuring the concentrations of dissolved organic/inorganic carbon (DOC/DIC) in the soil solutions.

Soil C concentrations were significantly higher in manure plot (ca. 9.5 %), compared to chemical fertilizer and no-fertilizer plots (ca. 8.4 – 8.9 %), probably due to the highest C inputs (4.0 Mg C $ha^{-1}$). The $CH_4$ fluxes increased with decreasing soil Eh after flooding, while $CO_2$ fluxes displayed the opposite pattern. There was no significant difference in $CH_4$ fluxes between manure and chemical fertilizer plots, while $CO_2$ fluxes were slightly higher in manure plot. This is supported by significantly higher microbial activities of cellulose decomposition and higher microbial biomass. We found that ca. 80 % of annual C output (3.6 to 4.5 Mg C $ha^{-1}$) was derived from $CO_2$ emission during the season after drainage and fall plowing in all plots. Organic matter application increased DOC/DIC concentrations in soil solutions, but DOC/DIC fluxes were even smaller than gas fluxes. Incorporation of fresh rice straw residues by fall plowing activated $CO_2$ emission after drainage, and the annual C outputs were roughly equal to C inputs even in manure plot. This suggests that application of organic matter could maintain soil C storage, but organic matter amendment for long term also increases microbial biomass and decomposition activity, especially in the season after drainage. Our findings highlight the importance of decreasing $CO_2$ emission after drainage to increase soil C storage by manure application in the Andisol paddy fields, while decreasing $CH_4$ emission after flooding also contributes to mitigate global warming.

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# Hybrid machine-learning and process-based regional crop modelling to improve rice production strategies in data-limited conditions: a case study of Lao PDR

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## ABSTRACT

Rice production in the Lao People's Democratic Republic is fundamental to national food security, but many aspects of its productivity and environmental impacts (such as $CH_4$, $N_2O$, NO, $NH_3$ emissions) are under-explored because systematic monitoring and comprehensive datasets are scarce. To address this, we developed a novel spatially explicit and cost-effective rice crop modelling framework by coupling the Decision Support System for Agro-technology Transfer (DSSAT) model with a particle swarm optimization (PSO) algorithm for data gap-filling to simulate rice growth and associated environmental impacts across Laos, from 2012 to 2022. Utilizing available statistical yield records for model calibration, we quantified rice yields, gas emissions and nitrogen loss pathways under contrasting water regimes in wet-season rain-fed rice systems. At the province level in Laos, fertilizer response curves show that high fertilizer prices relative to rice prices depress the economic optimum N application rate. A national guidance band of 25~30 kg N/ha with province-specific adjustments (reductions in 13 provinces and modest increases in a few) can increase farmers' profits while sustaining high nitrogen use efficiency (NUE). Our findings highlight Laos' potential advantages in advancing green rice production while underscoring the seasonal trade-offs in resource use efficiency and environmental outcomes. The proposed PSO-DSSAT framework offers a transferable tool for supporting sustainable rice management in regions with limited data coverage.

**Keywords:** Lao rice systems; DSSAT; particle swarm optimization; nitrogen management; greenhouse gas emissions; economic optimum

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# Pedogenesis Shapes the Basis of Sustainability of Paddy Soils

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**ABSTRACT**

Paddy soils are widely distributed in the world especially in East and Southeast Asia, Africa and Latin America, feeding more than a half of global population which means have contributed substantially to global food security. The sustainable use of this precious soil resource is extremely important for the generations to come. Though regular rice soil management practices including irrigation, plowing and fertilization affect fundamentally rice productivity, the assessment of the sustainability of rice soils is often neglected.

Through extensive studies in various paddy soils regions of China, we find that long term soil changes, i.e., soil changes through pedogenetic processes are dramatic and have fundamental impacts on soil health conditions, in terms of their changes in soil components and nutrient-binding capacity as well as their resilience in respond to possible artificial management. Clay loss, iron transformation and translocation, lowering of cation exchange capacity all indicate a potential yet invisible degradation, while generating secondary nutrient dissipation to environment and causing neighboring water quality changes.

It is an obvious task to examine long term changes of soil quality through the perspective of soil genesis of paddy soils for a sound soil health assessment.

**Key words:** Paddy Soil, Sustainability, Pedogenetic Process, Soil Health

**Acknowledgments**

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# Methane production potentials and methanogenic communities in winter-flooded rice paddy soils

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**ABSTRACT**

Winter-flooded rice paddies are important methane emission sources. As the second most prominent greenhouse gas after carbon dioxide, methane exerts a significant impact on global warming. Therefore, investigating the methane production potential of winter-flooded rice paddy holds considerable scientific significance. Soil samples from the 0-l0 cm layer of winter-flooded rice paddy were collected during the rice tillering stage for anaerobic incubation. Methane concentrations were dynamically determined using gas chromatography (GC) to calculate methane production rates, while high-throughput sequencing were employed to determine the changes in microbial communities. The results indicated that winter-flooded rice paddy soils possessed significant methane production potentials. The methane production rates first increased and then decreased over time, with the maximum rate reaching 24.32 ng g_1 day_1. After 34 days of incubation, the relative abundance of methanogens in the soils showed a converging trend: the relative abundance of the methanogen genus *Methanobacterium* decreased, whereas that of *Methanosarcina* exhibited a substantial increase, suggesting that the latter may have played a crucial role in the methane production process. The decrease in methane production rate may reflect the substrate limitations as well as the methane consuming processes in oxygen restricted environments. Thus we further checked the changes in the communities of sulfate-reducing bacteria (SRB), aerobic methane-oxidizing bacteria (MOB), and anaerobic methane-oxidizing bacteria (ANME). SRB showed varying degrees of abundance increase. The relative abundance of Type I MOB significantly increased overall but decreased in some cases, while Type II MOB exhibited a distinct decreasing trend. The relative abundance of ANME declined remarkably. These phenomena imply that these microbial groups may also be involved in methane metabolism, while the methane production process exerted a significant inhibitory effect on most aerobic MOB, ANME, and other microorganisms. Furthermore, soil factors such as temperature, moisture content, pH, and texture exerted varying influences on methane emissions from winter-flooded rice paddy soils. In conclusion, winter-flooded rice paddy soils possess considerable methane production potential, and *Methanosarcina* is the key methanogen.

**Key words:** methane production potential; winter-flooded rice paddy soil; greenhouse gases; methanogens; high throughput sequencing

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# Synergistic Effects of Water and Straw Management on Greenhouse Gas Dynamics and Carbon Sequestration in Subtropical Rice Ecosystems using Multichannel Automated Chamber System

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## ABSTRACT

Rice cultivation in subtropical Asia is a significant source of anthropogenic methane ($CH_4$) while offering potential for soil organic carbon (SOC) sequestration. This study investigated the interactive effects of water management and rice straw practices on greenhouse gas (GHG) emissions and SOC dynamics. Field experiments were conducted from 2024 to 2025 at the Ankang Experimental Farm, National Taiwan University (*Oryza sativa L.* cv. Taoyuan No. 6), employing a multi-channel automated chamber system for high-frequency, continuous monitoring of $CH_4$ and $N_2O$ fluxes. Six management scenarios were evaluated, combining two irrigation regimes conventional flooding (CF) and alternate wetting and drying (AWD) with three rice straw treatments including rice straw removal (-RS), incorporation (+RS), and rice straw cover (RS cover).The continuous monitoring revealed distinct temporal dynamics; straw input (+RS and RS cover) significantly increased $CH_4$ emissions by providing organic carbon substrates (DOC), with temporal shifts in emission intensity between the early and late rice seasons. In contrast, $N_2O$ emissions peaked sharply following fertilization and drainage events, with the RS cover treatment under AWD exhibiting the highest fluxes (21.90 g/ha/day in 2024), indicating complex carbon nitrogen coupling process. Water management proved essential for mitigation; except during periods of extreme rainfall, AWD consistently reduced $CH_4$ emission factors, achieving a 53% reduction in the 2025 season (1.70 kg/ha/day under AWD+RS vs. 3.62 kg/ha/day under CF+RS). Notably, the AWD+RS cover strategy achieved the lowest Greenhouse Gas Intensity (GHGI) of 0.69 t-$CO_2$eq/t grain in 2025, indicating its superior efficiency in minimizing the climate footprint per unit of yield. However, a divergence was observed in long-term carbon sequestration potential; linear regression of SOC stocks (2024–2025) confirmed that AWD+RS successfully promoted significant carbon storage ($y = 3.7x + 57$, $R^2 = 0.43$), whereas AWD+RS cover exhibited no significant temporal trend ($y = -0.42x + 71$, $R^2 = 0.004$). These findings demonstrate that while AWD+RS cover is optimal for immediate emission intensity reduction, AWD+RS incorporation provides a more robust pathway for long - term soil carbon buildup; thus, integrating AWD with optimized rice straw management offers a synergistic solution to balance productivity and soil health while effectively mitigating the climate footprint of subtropical rice cultivation

**Keywords:** greenhouse gas emissions, methane, nitrous oxide, carbon dynamics, nitrogen dynamics, rice straw management

# Mechanisms of Rice Root Iron Plaque-Induced Greenhouse Gas Emissions in Paddy Soils

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**ABSTRACT**

Rice root iron (Fe) plaque, a ubiquitous mineral coating at the root-soil interface, plays a critical but complex role in regulating greenhouse gas (GHG) emissions from paddy soils. This study integrates findings from multi-scale experiments to elucidate the coupling mechanisms between Fe plaque and the turnover of carbon (C) and nitrogen (N), specifically driving carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) emissions. First, regarding $CO_2$, we hypothesized that Fe plaque induces hydroxyl radical (OH) generation, which disrupts the organic carbon protection mechanism. Our results demonstrated that Fe plaque significantly increased OH concentrations via Fenton reactions. This oxidative burst degraded phenolic compounds, thereby disrupting the "enzyme latch" mechanism and accelerating soil organic carbon (SOC) mineralization and $CO_2$ emissions. Second, regarding $CH_4$, we investigated the role of semi-conductive minerals. We found that crystalline Fe oxides (specifically hematite) within the plaque facilitate extracellular electron transfer (EET) between methanogenic archaea (e.g., Methanosarcina) and their syntrophic bacterial partners (e.g., Geobacter). This mineral-mediated electron transfer significantly enhanced syntrophic methanogenesis, leading to elevated CH4 emissions in Fe plaque-rich soils. Third, regarding $N_2O$, we explored the coupling of Fe redox cycling and denitrification. Fe plaque acts as a hotspot for $N_2O$ emissions. Our evidence indicates that Fe(II) accumulated in the plaque serves as an electron donor for denitrification. The process of Fe(II) oxidation-coupled denitrification was identified as the primary driver for the increased N2O release. In conclusion, rice root Fe plaque is not merely a passive barrier but an active biogeochemical hotspot that simultaneously promotes $CO_2$, $CH_4$, and $N_2O$ emissions through distinct abiotic (Fenton reaction, semi-conduction) and biotic (syntrophy, denitrification) pathways. Regulating Fe plaque formation through soil management could be a potential strategy for mitigating combined GHG emissions from paddy agriculture.

**Acknowledgments**

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# Field investigation for 11 years revealed periodic fluctuations in the abundance and composition of bacterial and archaeal communities in paddy-upland rotational field

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## ABSTRACT

Paddy-upland rotation has become common in the world. Since field managements are fundamentally different between upland cropping and paddy rice cultivation, paddy-upland rotation must have impacted the soil biological properties, compared with the mono-cropping of paddy rice. However, it has not been investigated well how long-term paddy-upland rotation affects the dynamics and interrelationships of soil microbial communities in the soil. In the present study, we analyzed the dynamics of abundance and composition of bacterial and archaeal communities, mainly focusing on the microbes involved in the redox cycles of nitrogen, iron, sulfur, and carbon (methane), in an experimental field under two- or three-year cycle of paddy-upland rotation in Japan over the course of 11 years.

A long-term experimental field for paddy-upland rotation system in the northeast region of Japan was investigated in 2012–2022. A rotational system has been implemented in the field since 2000, in which rice and soybean have been cultivated every two or three years (rotational plot). As a comparison, a consecutive paddy field was examined in a field neighboring the rotational field (control plot). Bulk soil was taken at 5–10 cm depth before, during, and after rice or soybean cultivation period. The abundances of total bacteria, denitrifying bacteria, canonical ammonia-oxidizing bacteria, ammonia-oxidizing archaea, complete ammonia oxidizing (comammox) bacteria, *Geobacteraceae* (iron reducers), *Anaeromyxobacteraceae* (iron reducers), *Gallionellaceae* (iron oxidizers), sulfate-reducing bacteria, sulfur-oxidizing bacteria, methanogenic archaea, and methane-oxidizing bacteria were quantified by real-time PCR. The composition of bacterial community was analyzed by amplicon sequencing analysis of bacterial 16S rRNA genes.

Quantitative PCR analysis showed distinct fluctuations specific to the respective microbial groups between the paddy-upland rotation. In particular, the abundance of *Geobacteraceae* and *Gallionellaceae* drastically decreased after conversion from paddy rice to upland cropping, but their abundances recovered after re-conversion from upland to paddy rice cropping within a year. The amplicon sequencing analysis of bacterial 16S rRNA genes in the field revealed that community composition in the rotational plots was phylogenetically distant from that in the control plots, but the composition was periodically fluctuated between the years of paddy rice cultivation and upland cropping in the rotational plots. The present study showed that bacterial and archaeal communities have changed their community structures according to the periodic fluctuation of oxic and anoxic soil conditions associated with the paddy-upland rotation by adapting their metabolic activities to the soil conditions depending on their physiological features.

# Domesticated rice alters the rhizosphere microbiome, reducing nitrogen fixation and increasing nitrous oxide emissions

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**ABSTRACT**

Crop domestication has boosted global food security but intensified agricultural reliance on chemical inputs, creating environmental trade-offs in soil ecosystems. Rhizosphere microbiomes drive soil nitrogen (N) cycling, a process central to both crop productivity and greenhouse gas emissions, yet how domestication reshapes these microbial functions remains understudied. Shotgun metagenomics and real-time PCR reveal a higher abundance of N-fixing genes in the wild rice rhizosphere microbiomes. Validation through transplanting rhizosphere microbiome suspensions shows the highest nitrogenase activity in soils with wild rice suspensions, regardless of planted rice type. Domesticated rice, however, exhibits an increased number of genes associated with nitrous oxide ($N_2O$) production. Measurements of $N_2O$ emissions in soils with wild and domesticated rice are significantly higher in soil with domesticated rice compared to wild rice. Comparative root metabolomics between wild and domesticated rice further show that wild rice root exudates positively correlate with the frequency and abundance of microbial N-fixing genes, as indicated by metagenomic and qPCR, respectively. To confirm, we add wild and domesticated rice root metabolites to black soil, and qPCR shows that wild rice exudates maximize microbial N-fixing gene abundances and nitrogenase activity. Preliminary genetic evidence (from QTL mapping) further suggests a host genetic control governing the recruitment of these beneficial microbes, providing a scientific foundation for future breeding strategies aimed at reshaping the rhizosphere microbiome for more sustainable crop production.

# Denitrifier community responses to irrigation and straw management in subtropical paddy soils

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**ABSTRACT**

Rice paddies are important sources of greenhouse gases (GHGs), particularly methane ($CH_4$) and nitrous oxide ($N_2O$). While $CH_4$ emissions dominate under anaerobic conditions, mid-season drainage or intermittent irrigation can enhance $N_2O$ production through intensified nitrification–denitrification cycles. This study investigated the interactive effects of irrigation regime and straw incorporation on $N_2O$ emissions and denitrifying microbial communities in a subtropical paddy field located in Xindian District, northern Taiwan. Four management treatments were established: conventional irrigation (CI), CI with straw return (CI+S), alternate wetting and drying (AWD), and AWD with straw return (AWD+S).

About 0-10 cm of the surface soil samples were collected in triplicate from each practice plot during the sampling campaigns conducted between August and October 2023, before and after the basal, topdressing, and panicle fertilizer applications. Quantitative PCR (qPCR) and functional-gene amplicon sequencing were employed to determine the abundance and composition of denitrifiers (*nirS*, *nosZ-I*) of the colleceted soil samples. In addition, soil physicochemical properties were also analyzed and compared to the dominant denitrifying communities to evaluated their environmental niches with the farming practices.

Results showed that *Bradyrhizobium* was the dominant *nirS* type denitrifier across all treatments. Short-term straw incorporation increased soil labile organic carbon ($S_bOC$) but had limited influence on *nirS* type communities. In contrast, AWD significantly altered denitrifier composition and led to higher $N_2O$ emissions. Furthermore, qPCR results indicated that *nosZ-I* abundance was positively correlated with $S_bOC$, suggesting enhanced $N_2O$ reduction potential under carbon enriched conditions.

Overall, irrigation regime exerted a stronger control than straw return on both denitrifier community structure and $N_2O$ fluxes. These findings emphasize the importance of integrating microbial perspectives into sustainable paddy management strategies that balance $CH_4$ mitigation and $N_2O$ regulation.

**Acknowledgments**

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# Response of Rhizosphere Sulfur Utilization Microbiome to Rice Domestication

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## ABSTRACT

Sulfur is one of the main components of important biomolecules, playing a critical role in fundamental biological processes in both plants and microbes. In paddy soils, the dynamics of the sulfur cycle are predominantly governed by microbial activities, which are particularly intense and complex within the anaerobic environment of the rice rhizosphere. Our investigation reveals that the rhizosphere microbiome associated with wild rice (*Oryza barthii*, *O. rufipogon*, *O. nivara*) exhibits a superior capacity for sulfur nutrient mobilization compared to cultivated rice (*O. glaberrima*, *O. sativa*). Metagenomic and metabolomic analyses indicate that the wild rice rhizosphere supports a more diverse and functionally microbial community, characterized by an enriched repertoire of genes involved in key sulfur transformation pathways, such as sulfate reduction, sulfur oxidation, and organic sulfur compound metabolism. This enhanced genetic potential translates into a more dynamic and efficient sulfur cycle, ensuring improved availability of sulfur in soil for plant uptake. Furthermore, interactions between wild rice and the microbial community appear to be more robust and active, showing a positive and tightly coupled plant-microbe feedback relationship. Thus, the wild rice system demonstrates a more favorable and complex level of ecological integration for sulfur acquisition. This study aims to elucidate the underlying microbial mechanisms that confer this superior sulfur utilization in wild rice rhizosphere. By identifying key microbial taxa and defining the specific metabolic networks of wild rice rhizosphere, we seek to develop novel strategies for manipulating the rhizosphere microbiome of cultivated rice. The ultimate objective is to enhance the transformation and utilization efficiency of soil sulfur nutrients in agroecosystems, thereby reducing dependency on synthetic fertilizers and promoting sustainable rice cultivation practices.

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# Rare earth elements reshape the methanotrophs community to enhance the $CH_4$ oxidation in paddy fields

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## ABSTRACT

Methane ($CH_4$) is a potent greenhouse gas, and rice paddies are its main source of agricultural emissions. The methanotrophs in paddy soil serve as crucial "biofilters" for mitigating $CH_4$ emissions. While rare earth elements (REEs) are traditionally considered non-essential for living organisms, recent studies reveal that due to their similar ionic radius to calcium ions ($Ca^{2+}$) and stronger Lewis acidity, REEs can substitute $Ca^{2+}$ and serve as superior cofactors in methylotrophic and methane-oxidation pathways, thereby modifying conventional carbon metabolism. Nevertheless, how soil REE backgrounds influence $CH_4$ oxidation and shape methanotrophic communities in paddy fields remains poorly understood. This knowledge gap limits the development of REE-based strategies for mitigating agricultural $CH_4$ emissions.

To address this, we collected paddy soils with gradient REE background values spanning different climate zones, including mid-temperate, warm-temperate, and subtropical/tropical for microcosm incubation. Results show that increased REE background values enhance the $CH_4$ oxidation potential and the abundance of the *pmoA* gene, with a significant positive correlation observed between $CH_4$ oxidation potential and REE. In REE-differentiated paddy ecosystems, *Methylobacter* (Type I methanotrophs) dominates in temperate and increases significantly in high-background soils, whereas *Methylocystis* (Type II) represents the most abundant methanotrophs in warm temperate and subtropical/tropical. Variations in $CH_4$ oxidation functional genes are primarily and significantly influenced by mean annual temperature (19.79%) and total REE (11.11%). Active microorganisms involved in $CH_4$ oxidation process were successfully identified through $^{13}CH_4$-DNA-based stable isotope probing (SIP). Metagenomic analysis revealed that *Methylobacter*, *Methylosarcina*, and *Methylotuvimitrobium* are key active taxa, with *Methylotuvimitrobium* being specifically enriched in $^{13}C$-DNA fraction. At the functional gene level, the abundance of genes encoding particulate methane monooxygenase (*pmoA*), the REE-dependent methanol dehydrogenase (*xoxF*), and genes involved in formaldehyde assimilation (*fae*) were significantly higher in soils with high REE background values. Metagenomic binning of $^{13}C$-DNA yielded 122 high-quality metagenome-assembled genomes (MAGs), four of which were identified as methanotroph-related MAGs (including *Methylobacter*, *Methylomonas*, and *Methylocystis*). Comparative analysis of metabolic pathways revealed significant differences in methane oxidation, formaldehyde dehydrogenation, and carbon assimilation pathways between methanotrophs inhabiting high and low REE background soils.

These findings not only deepen our understanding of the role of metallic elements in the global carbon cycle but also provide important theoretical support for developing REE-based strategies to achieve $CH_4$ mitigation in rice paddy production.

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# Isolation, characterization and identification of culturable methane-oxidizing bacteria inhabiting paddy field ecosystem

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**ABSTRACT**

Methane is a greenhouse gas and paddy fields are an important source of methane emission. Aerobic methane-oxidizing bacteria (MOB) inhabiting oxic microsites in the paddy field ecosystem play crucial roles in mitigating methane emission from paddy fields. Thus, it is important to reveal ecology of MOB in the ecosystem for prediction and control of methane emission from paddy fields. Communities of MOB in the ecosystem have been investigated well by analyzing genes specific for MOB. However, phenotypic and genotypic characterization of culturable MOB inhabiting the ecosystem mostly remains to be elucidated, which will provide useful information for understanding the ecophysiology of MOB in the ecosystem. In the present study, several strains of MOB were isolated from paddy field ecosystem, characterized, and identified at species level.

Four type I (*Gammaproteobacteria*) and nine type II (*Alphaproteobacteria*) MOB strains were isolated from seven compartments of a Japanese paddy field: floodwater, soil surface, bulk soil, rhizosphere soil, roots, basal stem of rice plants and rice stumps. Among the isolates, two type I and one type II MOB strains were further characterized and identified at species level. An isolate from floodwater, strain Fw12E-Y, belonged to the genus *Methylomonas* (type Ia), but showed distinctive physiological and phylogenetic features from the recognized species of the genus. The name *Methylomonas koyamae* sp. nov. has been proposed for the strain. Strain RS11D-Pr was isolated from rhizosphere soil and belonged to type Ib MOB in the family *Methylococcaceae*. The strain showed morphological, physiological, chemotaxonomic and phylogenetic characteristics distinguishing the strain from related genera of *Methylococcus–Methylocaldum–Methyloparacoccus–Methylogaea* clade in the family. The name *Methylomagnum ishizawai* gen. nov., sp. nov. has been proposed for the strain. A type II MOB strain, SS37A-Re, was isolated from surface soil and belonged to the family *Methylocystaceae*. The strain was closely related to the genus *Methylocystis* phylogenetically, but exhibited distinctive morphological, physiological, chemotaxonomic and phylogenomic features from the members of the genus *Methylocystis*. The name *Methylocystis iwaonis* sp. nov. has been proposed for the strain. We further focused on rice roots as an important hotspot of methane oxidation and isolated two, three and seven MOB strains belonging to the genera *Methylomonas, Methylocystis* and *Methylosinus*, respectively. Among the strains, two and two strains in *Methylomonas* and *Methylocystis*, respectively, represented putative novel species based on the phenotypic and genotypic characteristics. These findings indicate that diversity of culturable MOB in paddy field ecosystem is still open to be explored. Further efforts to cultivate, isolate and characterize MOB strains are needed for understanding ecophysiological features of MOB inhabiting oxic microsites in the ecosystem.

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# Organic rice cultivation boosts microbial carbon use efficiency by modulating soil nutrient availability and microbial resource acquisition strategies

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**ABSTRACT**

Organic cultivation represents an environmentally friendly agricultural practice with the potential to enhance soil microbial diversities and functions. However, the mechanisms by which soil microbial communities regulate microbial metabolic efficiency under organic cultivation remain to be elucidated. Herein, the rice rhizosphere soil samples from three sites in Northeast China were compared for the differences in soil chemical properties, microbial biomass, enzyme activities, and microbial community diversities between organic and conventional cultivation at different growth stages. We also analyzed the contributions of these factors to the changes in microbial carbon use efficiency (CUE). Results showed that organic cultivation increased soil pH and available nutrient contents, alleviated microbial carbon (C) and nitrogen (N) limitations, and consequently improved microbial stoichiometric homeostasis and CUE. Conversely, microbial enzyme activities were significantly higher in conventional cultivation than in organic cultivation, especially during the later stages of rice growth. This resource allocation strategy of microorganisms led to a reduction in microbial diversity, biomass, and ultimately decreased in microbial CUE. We identified that the content of soil available N and the threshold element ratio for C:N ($TER_{C:N}$) were most important predictors of microbial CUE. Further, network analysis and partial least squares path model (PLS-PM) revealed that the specific microbial assemblies with high *rrn* copy number enhance microbial CUE by increasing biosynthesis (Fig.1). This study underscores the potential of organic farming in enhancing soil microbial CUE to mitigate ecosystem carbon losses, providing valuable insights for optimizing land management strategies to achieve soil carbon sequestration and advance sustainable agricultural practices (Liu et al., 2026).

**Keywords:** Metabolic efficiency; Nutrient limitation; Organic cultivation; Paddy soil

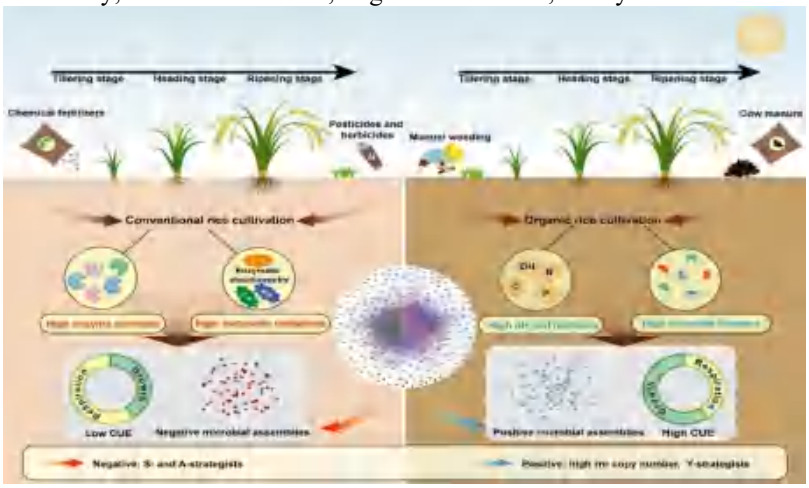



Fig. 1 Conceptual diagram of how organic rice cultivation enhances soil microbial carbon use efficiency (CUE)

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# Coordinated Action of Firmicutes and Bacteroidetes in Rice Straw Decomposition

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**ABSTRACT**

Global carbon storage in terrestrial ecosystems is about 1500 Pg per year, of which over 75-100 Pg carbon is returned to the atmosphere by soil microbial heterotrophic respiration. Rice paddy fields are widely distributed in Asia and provide a staple food for over half of the world populations. The input of plant-derived organic material amounts to 1.7 billion tons per year, most of which are left in fields and undergo anaerobic decomposition. This leads to an annual emission of 24-40 Tg methane into the atmosphere. However, the intricate process of plant biomass degradation by diverse soil microorganisms remains poorly characterized. Here I report a metagenomic research deciphering the mechanism of straw decomposition in a paddy soil.

The chemical analysis of 16-day soil microcosm incubation revealed that straw decomposition could be divided into an initial fast and then slowdown stages based on the dynamics of methane, short chain fatty acids, dissolved organic carbon and monosaccharides. Metagenomic analysis revealed that the relative abundance of glucoside hydrolase (GH) encoding genes for cellulose decomposition increased rapidly during the initial fast stage (3-7 days), while genes involved in hemicellulose decomposition increased in the slowdown stage (7-16 days). The increase of cellulose GH genes in the initial stage was derived mainly from *Firmicutes* while *Bacteroidota* contributed mostly to the increase of hemicellulose GH genes in the slowdown stage. Flagella assembly genes were prevalent in *Firmicutes* but scarce in *Bacteroidota*. Wood-Ljungdahl pathway (WLP) was ubiquitous in *Firmicutes* but not detected in *Bacteroidota*. However, *Bacteroidota* contained the largest proportion of total GHs and the highest number of CAZymes gene clusters (CGCs) across all metagenomes.

Overall, this study revealed a collaborating sequential contribution of microbial taxa and functional genes in the decomposition of straw residues in a paddy soil. *Firmicutes* with the property of mobility, WLP and cellulose decomposition could be mostly involved in the initial breakdown of straw polymers, while *Bacteroidota* became abundant and possibly responsible for the decomposition of hemicellulosic polymers during the later stage.

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# Irrigation management drives the niche differentiation and metabolic versatility of ammonia-oxidizing archaea in paddy soils

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**ABSTRACT**

Water-saving irrigation is increasingly adopted in rice cultivation to conserve water, improve fertilizer-use efficiency, and mitigate methane emissions. However, the associated drying–rewetting cycles can intensify nitrification, thereby increasing the risk of nitrate loss and nitrous oxide ($N_2O$) emissions. A mechanistic understanding of how irrigation regimes shape ammonia-oxidizing microorganisms is therefore essential for designing effective mitigation strategies. Here, we investigated paddy soils subjected to a decade of contrasting irrigation managements (water-saving irrigation and continuous flooding) using metagenomics, genome-resolved reconstruction, and comparative functional profiling. Metagenomic analyses revealed significantly higher abundances of ammonia-oxidation genes under water-saving irrigation, indicating enhanced nitrification potential. Across all soils, ammonia-oxidizing archaea (AOA) were the dominant ammonia oxidizers. We reconstructed 26 high-quality *Nitrososphaeria* metagenome-assembled genomes (MAGs) and found that water-saving irrigation supported higher AOA *Nitrososphaeria* diversity spanning six family-level clades (including NP, NT-beta, and multiple NS clades), whereas continuous flooding harbored a less diverse assemblage dominated by NT-alpha and a non-AOA *Nitrososphaeria* lineage. Comparative genomics further revealed irrigation- and lineage-linked metabolic differentiation: AOA from water-saving soils showed greater genomic potential for urea utilization and osmoregulation (e.g., $K^+$ transport systems and $Na^+/H^+$ antiporters) and were enriched in carbohydrate-active enzyme (CAZyme) genes, suggesting broader organic nitrogen and carbon acquisition capacities and adaptation to moisture fluctuations. In contrast, AOA from continuously flooded soils were enriched in $Mn^{2+}/Fe^{2+}$ transporters, consistent with adaptation to reducing conditions. Co-occurrence network analysis indicated that AOA in the water-saving module were embedded in consortia linking carbon, nitrogen, and sulfur cycling, showing positive associations with *Nitrospiraceae*, *Blastocatellia*, *Desulfobacterota*, and *Methylomirabilales*, whereas flooded-soil AOA were primarily associated with heterotrophic taxa that may contribute to substrate supply. Finally, irrigation regulated nitrate-reduction pathway partitioning: water-saving soils were enriched in denitrification genes (*nirS*/*nosZ*), whereas flooded soils showed higher *nrfA*, indicating DNRA dominance. Collectively, these results demonstrate that irrigation management imposes strong selective pressure on AOA lineages and their metabolic strategies, reshaping the coupling among nitrification, nitrate-reduction pathways, and broader biogeochemical interactions in fertilized paddy soils.

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# Nitrogen fertilization increases rice productivity at the expense of endophytic bacterial community stability and diversity

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**ABSTRACT**

Nitrogen (N) fertilization is indispensable for ensuring global food security by enhancing rice productivity; however, its ecological impact on the intricate assembly of rhizosphere and endophytic bacterial communities remains insufficiently characterized. This study utilized a pot experiment involving two rice cultivars (Longjing 29 and Longjing 39) subjected to four progressive N application rates (0, 40, 80, and 160 mg/kg soil) to systematically evaluate the responses of plant growth and associated microbial communities. Our findings demonstrate that while increasing N levels significantly promoted rice biomass, grain yield, and cumulative N uptake, it simultaneously induced a substantial decline in bacterial alpha diversity across the bulk soil, rhizosphere, and particularly the endosphere. These negative effects were most pronounced during the critical grain filling and maturity stages, suggesting a time-dependent sensitivity of the microbiome to N enrichment. The root endosphere exhibited the highest sensitivity to N inputs. Specifically, elevated N levels favored the expansion of *Proteobacteria* while significantly suppressing key plant growth-promoting bacteria (PGPB) such as *Geobacter*, *Bradyrhizobium*, and *Caulobacter*. Conversely, the relative abundance of potential opportunistic pathogens, including *Aeromonas* and *Stenotrophomonas*, increased under high-N conditions. Furthermore, co-occurrence network analysis indicated that endophytic bacterial communities became significantly less stable and more vulnerable to environmental disturbances compared to those in the rhizosphere and bulk soil. These results reveal a critical ecological trade-off: while intensive N fertilization maximizes short-term rice yields, it disrupts the structural integrity and homeostatic stability of the internal microbial community (Fig.1). Such dysbiosis may compromise long-term plant systemic health and overall N use efficiency. This study underscores the urgent need for optimized fertilization strategies that balance crop productivity with the maintenance of a healthy and resilient crop-associated microbiome in sustainable agricultural systems.

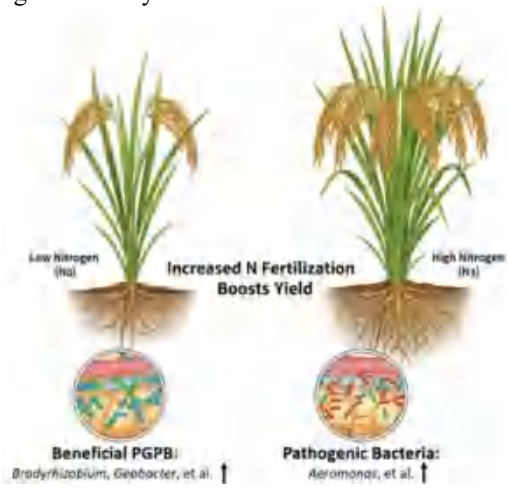



Fig.1 Conceptual trade-off between nitrogen-induced rice yield enhancement and endophytic bacterial community stability

**Keywords:** Nitrogen fertilization; Endophytic microbiome; Plant growth-promoting bacteria; Pathogenic bacteria; Rice

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# Effects of nitrogen application on rhizosphere microorganisms, metabolites, and plant growth of rice under controlled irrigation in paddy fields

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## ABSTRACT

**Background:** Aiming at the problems of frequent seasonal drought and weak productivity in paddy fields in Southwest China. This study focused on the characteristics and functions of rhizosphere microbial communities, the content of rhizosphere metabolites and the driving effects of rhizosphere microenvironment on rice growth and development. The purpose was to clarify the regulation mechanism of nitrogen application under controlled irrigation in paddy fields on rhizosphere microenvironment and rice development.

**Methods:** Randomized block design was used in the experimental area (n=4). A total of five treatments were set up, namely, no N treatment (FCK) under traditional flooding irrigation (FI), and four N application levels under controlled irrigation (CI), including no N application (CCK), low N application (90 N kg $hm^{-2}$, CN1), moderate N application (135 N kg $hm^{-2}$, CN2) and high N application (180 N kg $hm^{-2}$, CN3). The method of combining field experiment and omics analysis. We explored the structural composition, diversity changes and functional expression of rhizosphere microbial communities under different treatments at heading and mature stages; analyzed the species and contents of rhizosphere metabolites and the response characteristics of key metabolic pathways; revealed the driving effect of rhizosphere microenvironment (soil-microbial-metabolite) on plant growth and yield formation of rice.

**Results:** Nitrogen application significantly improved the physicochemical properties of paddy soil under controlled irrigation, and the soil AK, MBN, MBC and $NO_3^-$-N were significantly improved under the treatment of 25% nitrogen reduction (CN2). Based on metagenomic data, N application significantly increased the diversity of rhizosphere microbial communities under controlled irrigation paddy fields. The abundance of dominant microorganisms also changed significantly under different treatments, of which the relative abundance of *Hydrogenophaga* and *Sphingobium* was significantly increased by 107.10% and 84.48% under CN3 treatment ($P<0.05$), and *Nocardioides* was higher under CN2 treatment, with an increase of 16.20%, respectively.The dominant functions of rice at heading stage and mature stage were consistent, of which Amino acid metabolism (12.46%~12.76%) and Carbohydrate metabolism (11.00%~11.96%) had the highest functional abundance. Based on metabolomics results, there was a significant difference in the composition and content of rhizosphere metabolites between heading stage and mature stage of rice. It was showed the content of organic acid decreased and lipid increased from heading stage to mature stage of rice. Meanwhile, the content of Nucleic acids, Carbohydrates and Antibiotics were significantly increased under CN2 treatment at mature stage. Finally, the rhizosphere microenvironment directly or indirectly drives rice growth through the synergistic effect of soil-microorganism-metabolites. Moderate nitrogen application can optimize the rhizosphere microenvironment and positively promote plant growth of rice.

**Conclusions:** This study revealed the comprehensive effects of nitrogen regulation on 'soil-microorganism-metabolite-plant' under controlled irrigation in paddy fields, explored the changes of rhizosphere microenvironment, and proposed the best water and nitrogen regulation mode (CN2) in the main rice producing areas of Southwest China. The micro-ecological mechanism of water and nitrogen regulation in paddy fields on high yield and efficient utilization of water-nutrient of rice was clarified. This will provide theoretical basis and technical support for increasing the productivity of paddy fields and improving the rhizosphere microecological environment.

# Synergistic Effects of Integrated Amendment Practices on Soil Health and Crop Productivity in a Newly Reclaimed Cultivated Land

**ABSTRACT**

Newly reclaimed cropland commonly faces issues such as poor soil structure, low fertility, and insufficient biological activity, which constrain crop production. However, the comprehensive effects of different soil improvement measures on various aspects of soil health and their relationship with crop growth remain unclear. To address this, a field experiment was conducted with the following treatments: chemical fertilizer alone (NPK), bio-organic fertilizer (MF), two integrated improvement measures (MCN and MCN_2), and a blank control (CK). Both the bio-organic fertilizer and the two integrated measures were amended with an equivalent amount of organic matter. The integrated measures comprised an organic material source combined with modified biochar, minerals, and microbial inoculants. The study aimed to investigate the effects of these different treatments on soil physical, chemical, and biological properties as well as wheat growth, and to identify key soil factors driving yield improvement. Measurements at wheat maturity showed that, compared to the NPK treatment, the MCN treatment was most effective in improving soil structure (bulk density reduced by 0.14 g/cm³), alleviating acidification (pH increased by 0.87 units), enhancing fertility (soil organic matter increased by 4.43 g/kg, the ratio of available phosphorus to total phosphorus increased by 3.5%, and calcium content increased by 0.07%), and boosting microbial richness (Observed, Chao1, and Shannon indices increased by 28.6%, 28.3%, and 7.3%, respectively) and activity (activities of β-glucosidase, leucine aminopeptidase, and β-N-acetylglucosaminidase increased by 106.1%, 29.7%, and 60.0%, respectively). LEfSe analysis revealed that the integrated treatments enriched nitrogen-fixing bacteria (e.g., *Mesorhizobium*), organic matter-decomposing bacteria (e.g., *Fibrobacteraceae*, *Pseudohongiellaceae*), and beneficial *Bacillus* strains (e.g., *Blastocatellaceae*). Furthermore, the MCN treatment significantly increased wheat plant height, stem diameter, and yield, resulting in yield increases of 294.3% and 16.5% compared to the NPK and MF treatments, respectively. Correlation analysis indicated that grain yield was significantly correlated ($p < 0.05$) with soil organic matter, total nitrogen, total phosphorus, available phosphorus, calcium, manganese, the Shannon index, and bacterial phyla including *Pseudomonadota*, *Verrucomicrobiota*, and *Actinomycetota*. Yield also showed positive correlations with soil pH and the activities of sucrase, β-glucosidase, leucine aminopeptidase, and β-N-acetylglucosaminidase. Partial least squares path modeling identified the core pathway as "Improvement measures → Enhanced soil fertility (increased organic matter and mineral elements) → Microbial regulation → Yield promotion." In conclusion, the integrated measure combining organic materials with modified biochar, minerals, and microbial inoculants can rapidly improve soil health and crop yield in newly reclaimed cropland through synergistic multi-pathway effects, representing an effective strategy for achieving rapid maturation and ensuring high, stable yields in such soils.

**Key words:**Newly reclaimed cropland, soil improvement, soil health, crop productivity, synergistic effect

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# Impact of microbial interactions on aerobic methanotrophs and methane oxidation activity in soils

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**ABSTRACT**

Accumulating evidence underscores the importance of microbial interactions in influencing community dynamics and modifying microbially mediated processes. However, empirical data detailing the effects of these interactions on the communities and activities of aerobic methanotrophs in soil environments are still limited. First, we examined the methane ($CH_4$) oxidation rate and active atmospheric $CH_4$-oxidizing methanotroph communities in two grassland ecosystems. Redundancy, correlation, and random forest analyses revealed that the carbon dioxide ($CO_2$) production rate is a key predictor of active methanotroph community composition and atmospheric $CH_4$ oxidation activity. An incubation experiment with glucose amendment demonstrated that glucose addition enhanced heterotrophic microbial respiration and suppressed atmospheric $CH_4$ oxidation. This study demonstrates that the $CO_2$ production rate is a crucial factor influencing atmospheric $CH_4$ oxidation activity in grassland ecosystems. It also indicates that interactions between methanotrophs and other heterotrophs affect methanotroph activity in these ecosystems. Subsequently, we analyzed in-situ greenhouse gas (GHG) emissions and clarified potential relationships between active microbes involved in methane oxidation and nitrification in grassland soils. DNA-based stable isotope probing (SIP) incubation experiments revealed that competition between active methanotrophs and nitrifiers suppressed $CH_4$ oxidation activity. Lastly, the impact of microbial interactions within and across trophic levels on $CH_4$ oxidation was further substantiated through analyses of methane-driven food webs, employing $^{13}C$-$CH_4$ based SIP and metagenomic sequencing. Metagenomic data and incubation experiments indicated that metabolites from *Hyphomicrobium* (cobalamin) and *Micromonosporaceae* (terpenoid volatiles) respectively promoted and inhibited $CH_4$ oxidation activity. Furthermore, predation on methanotrophs by myxobacteria, protists, and viruses also inhibited $CH_4$ oxidation activity. In conclusion, our findings offer empirical evidence of the substantial impact that microbial interactions have on aerobic methanotrophs and $CH_4$ oxidation activity in soil environments.

# From Genes to Gas: Dynamics of Active Methanogenic Food Webs in Rice Paddies

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## ABSTRACT

Methane production in rice paddies is governed by the coordinated activity of bacteria, methanogens and virus rather than by methanogen alone. Integrating time-resolved metatranscriptomics and metagenomcis, we found that carbon flow toward methane is shaped by dynamic interactions among fermentative bacteria, syntrophic partners, methanogens, and their associated viruses, forming a responsive anaerobic food web. Environmental drivers, including temperature, salinity, and nanoplastic contamination, reorganize both transcriptional activity and network connectivity, thereby reshaping methanogenic pathways and methane production rates. We further demonstrate pronounced temporal shifts and pathway flexibility within dominant methanogens, particularly Methanosarcina, underscoring functional plasticity as a key stabilizing mechanism under fluctuating conditions. Notably, virus–host interactions provide an additional layer of regulation on methanogen population dynamics and activity. Together, these findings establish an activity-centered microbial framework for understanding methane metabolism in rice paddies, highlighting the central role of active microbial food webs in controlling greenhouse methane emissions under environmental change.

**Acknowledgments**

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# The functional divergence and biogeographic patterns of electron-transferring flavoprotein (Etf) in paddy soil

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**ABSTRACT**

Rice fields, distributed across diverse climatic zones worldwide, serve as primary agricultural source of atmospheric methane emissions that substantially contribute to global climate change. Methane production through anaerobic methanogens is constrained by thermodynamic limitations during syntrophic oxidation of fatty acid, a process that relies on syntrophs and methanogens. The flavin-based electron bifurcation (FBEB) mechanism, mediated by the electron-transferring flavoprotein (Etf) enzyme, plays a pivotal role in energy metabolism by efficiently overcoming these thermodynamic constraints through enhanced energy transfer. However, the genetic diversity, functional differentiation mechanisms, and biogeographic distribution patterns of EtfAB remain poorly understood. To address these gaps, we integrated advanced computational tools including machine learning algorithms, multi-omics data analysis, and AlphaFold3 software to comprehensively investigate the structural diversity, distribution characteristics, and evolutionary patterns of EtfAB sequence homologs. Based on the sequence-specific features of EtfAB, we elucidate the mechanism underlying flavin-based electron bifurcation mediated in energy metabolism of syntrophs. Additionally, we clarified the global geographic distribution of EtfAB within rice fields and its relationship with environmental factors. These findings will provide critical theoretical insights into the energy metabolism mechanism of methanogens in rice field and improve methane emission predictions.

**Keywords** paddy soil; syntrophs; electron-transferring flavoprotein (Etf); flavin-based electron bifurcation; biogeographic patterns

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# Divergent Methanogenesis in Chinese Paddy Soils Driven by Organic Matter Composition under Climate Warming

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**ABSTRACT**

Methane ($CH_4$) is a potent greenhouse gas, and microbial methanogenesis in paddy soils represents one of its major agricultural sources. Dissolved organic matter (DOM) serves as the most direct carbon substrate for soil microbes, yet how its inherent composition modulates the response of methanogenesis to warming remains poorly understood. We hypothesize that due to geographic heterogeneity in DOM characteristics, paddy soils will exhibit divergent methanogenic responses to temperature increase, leading to varied feedback under global warming. To test this, we conducted systematic anaerobic incubation experiments using 37 paddy soils collected across major rice-growing regions in China, across six temperature gradients (15℃,20℃,25℃,30℃,35℃,40℃). $CH_4$ production was monitored periodically, and DOM dynamics were characterized via 3D fluorescence spectroscopy. Two distinct response patterns emerged: Pattern I (22 soils) exhibited peak methanogenesis at 30~35℃ followed by a decline at 40℃, while Pattern II (15 soils) showed continuously increasing rates with temperature. These patterns correlated with initial DOM properties: Pattern I soils had significantly higher humification index (HIX), indicating more recalcitrant DOM, whereas Pattern II soils showed higher protein-like fluorescence, suggesting more labile, microbially derived substrates. Furthermore, after incubation at 40℃, DOM transformation pathways diverged significantly from those at lower temperatures, demonstrating that differential microbial utilization of DOM is closely associated with the bifurcation in methanogenic temperature response. This study establishes a significant correlation between DOM characteristics, its differential microbial utilization, and the observed dual-mode temperature response of methanogenesis. Future work integrating microbial community analysis will elucidate the underlying mechanisms and support the development of a predictive classification model, thereby improving the accuracy of $CH_4$ emission projections from paddy ecosystems under climate change.

**Keywords:** Methanogenesis, Paddy soil, Temperature response, Dissolved organic matter (DOM)

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# Microbial background for mitigating methane emission from rice fields

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**ABSTRACT**

Rice production is indispensable for food security, particularly in Asia, yet irrigated paddy agriculture is a major anthropogenic source of atmospheric methane, contributing roughly 8–10% of global emissions. Meeting rising food demand while reducing greenhouse gas outputs necessitates mitigation strategies that do not compromise crop yields. Methane emissions from rice fields result from anaerobic degradation of organic matter and are controlled by interactions among methanogenic production, methanotrophic oxidation, and transport processes mediated by soil and plant systems. Methane production is mainly driven by plant photosynthesis and the anaerobic degradation of organic matter in soil. Mitigation approaches targeting bulk soil focus on reducing the ratio of degradable organic matter to available electron acceptors. Avoiding or optimizing incorporation of rice straw and employing more recalcitrant amendments can significantly suppress methanogenesis. Increasing the availability of oxidants—such as ferric iron, sulfate, or nitrate—can inhibit methanogenic pathways through microbial competition, though nitrogen fertilizers pose trade-offs by potentially enhancing $CH_4$ production and elevating $N_2O$ emissions. Drainage strategies, including alternate wetting and drying, can markedly reduce CH4 formation while maintaining acceptable net global warming potential despite increased $N_2O$ fluxes. Biochar additions may further mitigate $CH_4$ emissions by modulating redox processes and microbial activity. At the level of plant photosynthesis, mitigation centers on restricting root-derived carbon allocation and increasing oxidative capacity. Cultivar selection and genetic engineering can shift photosynthate distribution toward grain rather than root biomass, simultaneously enhancing yield and limiting methanogenic substrate availability. Increasing $O_2$ transport and rhizospheric electron acceptors enhances both aerobic and anaerobic methane oxidation, while microbial manipulation—such as enrichment of methanotrophs or introduction of cable bacteria—shows emerging promise. Overall, the most effective mitigation strategies integrate soil management with plant-focused approaches, emphasizing electron acceptor optimization, organic matter control, and cultivar development. These methods offer substantial potential to reduce rice-associated $CH_4$ emissions without sacrificing productivity.

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# Effects of light on microbial community in the surface soil of a paddy field

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**ABSTRACT**

It is well known that sunlight exposure in paddy fields stimulates photosynthesis in algae inhabiting surface water, thereby contributing to soil fertility. However, knowledge of soil gas metabolism and microbial community responses in surface soils to light remains limited.

Flooded paddy soils exhibit characteristic stratification reflecting oxygen concentration. The peak daytime oxygen concentration occurs in the subsurface layer, and the diel oscillation in oxygen concentration in the surface soil is significantly greater than that in the surface water. Consequently, photosynthesis and subsequent respiration by microorganisms inhabiting the surface soil are sufficiently intense to influence biogeochemical cycles and microbial ecology.

Under light conditions, the surface soil of rice fields effectively suppresses $CO_2$ flux to the atmosphere, contributing to system recarbonization; algal photosynthesis further facilitates atmospheric $CO_2$ uptake. The dissolved oxygen profiles in the surface layer of flooded paddy soils change rapidly with light conditions, apparently influencing methane flux from the soil surface. Oscillations in oxygen profiles are also likely linked to iron cycling. Stable isotope probing with $^{13}CO_2$ showed that, among prokaryotes, diverse groups beyond cyanobacteria incorporated $^{13}C$ into the soil under light. Among eukaryotic microbes, green algae and diatoms were overwhelmingly dominant, while fungi, amoebae, and cercozoan flagellates also incorporated $^{13}C$, demonstrating a photosynthetic microbial food chain in the surface soil. Overall, our findings suggest that light irradiation plays a significant role in shaping biogeochemical cycles and microbial communities in the surface soil of a flooded paddy field.

# Beyond Nutrients: Minerals as Evolutionary Architects and Signaling Hubs in Soil Microbial Communities

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**ABSTRACT**

Minerals have long been regarded primarily as passive sources of nutrients or physical scaffolds in soils. However, our research demonstrates that they actively drive microbial evolution, shape community assembly, and regulate functional gene expression—even under nutrient-rich conditions. Through serial passage evolution experiments, we exposed soil-derived bacterial consortia to a spectrum of nutritive and non-nutritive minerals. The results reveal that mineral substrates consistently restructured communities, notably enriching rare taxa that serve as key agents of niche specialization and metabolic diversification, while abundant taxa maintained core ecosystem functions.

Expanding beyond compositional shifts, metatranscriptomic analyses uncovered that minerals such as kaolinite and olivine act as signaling entities, triggering the upregulation of genes involved in antibiotic biosynthesis, antibiotic resistance, and the degradation of complex organic matter. These responses reflect a form of microbial "memory," where mineral surfaces pre-activate adaptive pathways in anticipation of environmental challenges. Notably, even chemically inert minerals like quartz exerted selective pressures that reshaped community trajectories through physical interface effects.

Together, these findings reposition the mineralosphere as a dynamic microhabitat where abiotic properties govern biodiversity, functional redundancy, and evolutionary innovation. By integrating ecological and molecular perspectives, our work establishes minerals as central players in microbial adaptation—with important implications for soil health, biogeochemical resilience, and strategies in ecosystem management and restoration.

**Acknowledgments**

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# Effective suppression of methane emission using ethephon and polymer mixture

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**ABSTRACT**

Ethylene was known to have a strong inhibitory effect on microbial activity, including methanogens. However, ethylene, which is insoluble in water and has a gaseous form, could be utilized as a methanogenesis inhibitor in rice paddy fields. However, the potential of ethephon, which is a precursor of ethylene, as a methanogenesis inhibitor was verified to be utilized in rice cultivation condition. However, it is very unstable under high soil pH over 7. Under the flooded rice paddy, its chemical can convert into ethylene gas within 2-3 days, and therefore, it cannot be directly utilized as an amendment to suppress methane emission in rice field. To develop ethephon as a methanogen inhibitor which can utilize in rice cropping field, an inorganic amendment was developed by mixing with ethephon and polymer for controlling methylene release time. Four different water-soluble polymers (CMC, HEC, HEMC, & PVA) were selected. Ethephon was solubilized in polymer solution (1%, wt $v^{-1}$), mixed with gypsum ($CaSO_4$), and granulated using a disc fertilizer machine. In the flooded incubation test, which applied 1 mg $kg^{-1}$ of ethephon, CMC among the selected polymers was most effective to suppress methane emission, and then followed by HEMC, HEC, & PVA. In ethephon-CMC mixed treatment, methane flux significantly decreased with increasing ethephon application level. Half of methane flux was decreased by 0.5 mg $kg^{-1}$ of ethephon application. One more coating of pure CMC polymer solution on dried ethephon-CMC mixture increased methane suppression effect by 95% over the control. Therefore, the suppression effect of ethephon on methane emission could be more effectively enhanced by improving polymer applying practices. In conclusion, the formulation of ethephon with polymers can increase significantly methane emission, and this formulation could be utilized in developing low methane fertilizers and amendments.

**Keywords:** Sustainable agriculture, Methanogens, Methanotrophs, Plant growth compound, Ethephon

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# Contrasting water regimes reshape anaerobic denitrification-primed organic nitrogen mineralization

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## ABSTRACT

Conventional theory holds that soil flooding enhances denitrification by restricting oxygen diffusion and lowering redox potential, implicitly presuming that carbon and nitrogen availability for denitrification is comparable across soil moisture regimes once anaerobic conditions are established. Here, we challenge this assumption and propose a new mechanistic framework in which soil water status under anaerobic conditions governs the coupling between denitrification and organic nitrogen (SON) mineralization by regulating solute transport and microbial metabolic strategies, rather than denitrification intensity alone. Under strictly anaerobic conditions, we compared nitrogen transformation processes in paddy soils under fresh (60%WHC) and fully flooded (100%WHC) regimes using microcosm incubations. Although denitrification activity was comparable between moisture regimes, flooding markedly enhanced SON mineralization by 1.3–3.7 fold. This pattern indicates that soil moisture redirects nitrogen fluxes by reshaping the functional linkage between denitrification and SON decomposition. Under conditions allowing complete denitrification, SON mineralization was further stimulated, providing direct evidence for a denitrification-induced priming effect on SON decomposition under anaerobic conditions. However, this effect was mediated by distinct metabolic strategies. Flooded soils exhibited higher SON mineralization potential and ammonium assimilation capacity but lower abundances and transcriptional levels of denitrification genes, indicating a “high-mineralization–low gene investment” strategy. In contrast, fresh soils relied on higher denitrification gene expression to sustain comparable denitrification fluxes. Integrated multi-omics analyses revealed the microbial basis of this divergence. *Pseudomonas* served as the core active denitrifier across both moisture regimes, with *Azotobacter* as a secondary contributor, whereas soil moisture reshaped subordinate functional guilds. *Bacillus* and *Gammaproteobacteria* dominated denitrification in fresh soils, while *Schinkia* and *Oxalobacteraceae* prevailed under flooded conditions, reflecting moisture-driven niche replacement. Mechanistically, enhanced SON mineralization was driven by the decomposition of chitin and amino acid–containing compounds. Flooding increased the transcriptional activity of *Anaerolineae* and *Prolixibacteraceae* to promote chitin degradation and enhanced the expression of *Symbiodinium*, *Acidobacteriota*, *Vicinamibacterales*, and *Thermoanaerobaculaceae* to accelerate glutamate and glutamine decomposition. These processes continuously converted complex SON into bioavailable ammonium, supporting microbial biomass synthesis. Overall, this study establishes that under anaerobic conditions, soil moisture does not determine whether denitrification occurs, but instead controls nitrogen fate by regulating the coupling between denitrification and SON mineralization through solute transport and microbial metabolic partitioning.

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# Impact of land use and soil types on microbial $N_2O$ reduction potential mediated by nosZ communities

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**ABSTRACT**

Agriculture is the dominant source of global $N_2O$ emissions, how land use and soil type regulate nosZ communities and their role in microbial $N_2O$ reduction remains poorly understood. Here, we investigated how land use and soil type shape soil $N_2O$ reduction potential through the abundance, diversity, assembly, and interactions of nosZI and nosZII communities in paddy and upland soils across coastal China. Paddy soils exhibited significantly higher $N_2O$ reduction potential than upland soils, with soil type further modulating this potential within paddy systems, whereas no significant differences were observed among upland soils. Consistently, the absolute abundances of both nosZI and nosZII were markedly higher in paddy soils, indicating a greater intrinsic capacity for $N_2O$ reduction, although their relationships with $N_2O$ reduction potential differed between land-use types. While α diversity of nosZI and nosZII did not differ between paddy and upland soils, nosZI consistently showed higher diversity and broader ecological niche width than nosZII. Community assembly analyses further revealed a higher contribution of deterministic processes in nosZII communities, suggesting stronger environmental filtering. Co-occurrence network analyses demonstrated that $N_2O$ reduction potential was not associated with the network complexity of individual nosZI or nosZII communities, but was positively linked to enhanced cross-group interactions between nosZI and nosZII in paddy soils. In contrast, such functional coupling was absent in upland soils. Overall, our findings highlight land-use-driven microbial cooperation as a key mechanism regulating spatial variability in soil $N_2O$ reduction potential.

**Key words:** nitrous oxide reduction, nosZI, nosZII, land use, microbial interaction

# From DOM to Methane and Arsenic Release: Soil as a Key Control in Paddy Soils

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**ABSTRACT**

Soil texture fundamentally governs redox interactions among dissolved organic matter (DOM), methanogenesis, and arsenic (As) mobilization in paddy soils, yet the underlying mechanisms remain unclear. This study combined porewater geochemistry, DOM molecular characterization (3D-EEM and FT-ICR-MS), and microbial analyses (16S rRNA sequencing and metagenomics) to compare coarse loam and fine silt soils in the Jianghan Plain. Loam soils promoted stronger reducing conditions and accelerated decomposition of aromatic, polyphenolic, and nitrogen-rich unsaturated DOM compounds, which acted as key electron donors and ligands, enhancing Fe(III) reduction and As release. These molecular shifts corresponded to significantly higher methane production and porewater As in loam versus silt. Metagenomic and microbial profiling revealed enriched populations of methanogens, anaerobic methanotrophic archaea (*Ca. Methanoperedens*), and Fe/As-reducing bacteria, along with elevated gene abundances for methane cycling (mcrA, fwd) and arsenic transformation (arrA, arsM). Together, these components formed an integrated "methane cycling–arsenic reduction" network. Our findings highlight how soil texture modulates DOM reactivity and microbial redox processes, offering new mechanistic insight into methane-driven As mobilization and groundwater As risks in rice paddies.

**Keywords:** Paddy, Arsenic, Methane, Porewater

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# Discovery of iron-reducing diazotrophs in rice paddy soil and enhancement of nitrogen fixation by iron application

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**ABSTRACT**

Global agriculture relies heavily on nitrogen (N) fertilizers; however, excessive N fertilizer application causes serious environmental pollution. Developing crop production systems with reduced N fertilizer inputs is therefore essential and could be achieved by harnessing N-fixing microorganisms (diazotrophs) in agricultural soils. Through metatranscriptomic analyses and isolation studies, we discovered previously overlooked diazotrophs, *Anaeromyxobacter* and *Geobacter*, which are well-known iron-reducing bacteria predominant in paddy soils. We hypothesized that the addition of ferric iron oxides, serving as electron acceptors for iron-reducing respiration, could enhance the N-fixing activity of these bacteria in paddy soils. Consistent with this hypothesis, soil N-fixing activity significantly increased after the addition of ferrihydrite or $Fe_2O_3$ to laboratory soil microcosms and iron powder to paddy field soils. Here, with special References to iron-reducing diazotrophs, we performed $^{15}$N-DNA stable isotope probing (SIP) together with $^{15}$N-IRMS analysis of native and iron-applied paddy field soils to (i) identify active diazotrophs and (ii) quantify the amount of fixed N. SIP analysis revealed that *Anaeromyxobacter* and *Geobacter* were the most active diazotrophs in both native and iron-applied paddy soils. In addition, *Bacteroides*, known to exhibit iron-reducing activity, was identified as another active diazotroph in iron-applied soils. IRMS analysis revealed a significant increase in the amount of fixed N in iron-applied soils. Notably, in iron-applied paddy soils, these iron-reducing diazotrophs outcompeted methanogens for carbon substrates, thereby suppressing methane emissions.

Collectively, these results indicated that (i) the newly identified iron-reducing diazotrophs *Anaeromyxobacter* and *Geobacter* are primary drivers of N fixation in paddy soils and (ii) iron application enhances their activity, thereby increasing soil N inputs while simultaneously mitigating methane emissions. This study highlights a novel paddy soil management strategy that improves soil N fertility, sustains rice yields with reduced N fertilizer inputs, and lowers environmental nitrogen and carbon burdens.

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# Nitrous oxide acts as an alternative electron acceptor for microbial methane oxidation in oxygen-deficient microcosms

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## ABSTRACT

Submerged paddy fields are recognized hotspots for methane ($CH_4$) and nitrous oxide ($N_2O$) emissions. While thermodynamic calculations suggest the feasibility of anaerobic $CH_4$ oxidation coupled with $N_2O$ reduction (AMNR), the specific microbial drivers in these oxygen-deficient agricultural environments remain largely unclear. This study hypothesized that conventional aerobic methanotrophs could facilitate the AMNR process in paddy soils. We established microcosms using four typical soil samples collected from different latitudes in China (Acrisols, Gleysols, Luvisols, and Cambisols). Enrichment reactors were maintained with continuous $CH_4$ and $N_2O$ supply for over 400 days to cultivate functional microbes.

Results demonstrated that the AMNR process occurred in all paddy soil samples. A consistently high $N_2O$ reduction rate (5.37-6.24 umol·$g^{-1}$ dry soil·$d^{-1}$) was observed, strongly associated with $CO_2$ formation. The process exhibited two distinct phases: a rapid $N_2O$ reduction phase concurrent with $CH_4$ oxidation, followed by a slower reduction phase. $^{13}C$-$CH_4$ tracing confirmed that $CH_4$ oxidation was tightly coupled to $N_2O$ reduction under oxygen-deficient conditions. Contrary to expectations involving anaerobic methanotrophs like *Candidatus* Methylomirabilis, 16S rRNA sequencing and metagenomic analysis revealed that conventional aerobic methanotrophs, specifically members of the Methylocystis and Methylobacterium genera, were the keystone taxa. These methanotrophs dominated the bacterial community after long-term cultivation. Functional gene analysis indicated that these bacteria harbor the *nosZ* gene, suggesting they can directly reduce $N_2O$. Alternatively, they may support heterotrophic denitrifiers by providing fermentative intermediates as electron donors. Additionally, the stoichiometry of $N_2O$ reduction exceeded theoretical expectations for simple coupling, coinciding with the presence of nitrogen fixation genes (*nifH*, *nifD*) in the enriched methanotrophs, suggesting a potential interplay with nitrogen fixation.

In conclusion, this study identifies that conventional aerobic methanotrophs possess the metabolic flexibility to utilize $N_2O$ as an alternative electron acceptor in hypoxic paddy soils. This mechanism provides a novel perspective on the simultaneous mitigation of two potent greenhouse gases in agricultural wetlands.

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# The microbial community characteristics of soda saline-alkali paddy with flue gas desulfurization gypsum reclamation

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**ABSTRACT**

The extensive worldwide prevalence of saline-alkali soils presents a formidable challenge to both food security and environmental stability. Our previous study had well documented that the flue gas desulfurization gypsum long-term amendment saline-alkali paddy fields enhanced the soil microbial diversity and complexity (Liu et al., 2025), the subsequent migration and communication of these communities within the paddy soil - irrigation water - rice plant continuum need further research. Here, we conducted a long-term soda saline-alkali paddy amelioration experiment in China's Songnen Plain, comparing monoculture rice reclamation (PR) and flue gas desulfurization gypsum adding combined with cultivation rice reclamation (FGDG). Using 16S rRNA sequencing of paddy soil, irrigation water layer, and rice plant samples collected over reclamation 1-12 years, we characterized microbial diversity, composition, migration, and function. Results showed that FGDG significantly altered microbial community dynamics, reducing species replacement of beta-diversity in paddy soil and root endosphere alpha-diversity and inhibiting soil-to-root microbial migration while promoting endophytic interactions. Simultaneously, FGDG enhanced the paddy soil and irrigation water layer microbial community molecular ecological network modularity by changing the relative abundance of *Desulfosarcinaceae*, *Thiobacillus*, and *Anaerolineaceae*. Critically, FGDG application suppressed key methane production pathways and simultaneously enhanced sulfur cycling functions in soda saline-alkali paddy soil. Corroborated by soil salinity and nutrient analyses, this functional pivot was driven by FGDG-induced changes in soil chemistry—namely reduced pH and salinity and increased $SO_4^{2-}$, which gave sulfate-reducing bacteria a competitive advantage over methanogens. Our findings demonstrate that FGDG acts as a powerful ecological driver, engineering a stable, functionally specialized microbial ecosystem. This offers a sustainable strategy to improve soil health, mitigate greenhouse gas emissions, and enhance rice health in soda saline-alkali paddies with FGDG reclamation.

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# Effects of rice-mushroom rotation systems on soil fungal communities and rice yield

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**ABSTRACT**

Soil microorganisms are essential for crop performance, and crop rotation is a key practice for shaping soil microbial communities. Rice-mushroom rotation uses the paddy fallow period for edible mushroom production, but how this system modifies the soil microbiome and influences rice yield remains poorly understood. Here, we combined a long-term field experiment with pot assays to compare rice–mushroom and conventional rice–wheat rotations and to quantify their effects on rice biomass, soil properties and soil fungal communities. Rice-mushroom rotation significantly increased rice biomass relative to rice-wheat rotation, and this effect was associated with shifts in the resident fungal community, including higher relative abundance and richness of indigenous soil fungal taxa with plant growth-promoting functions. Moreover, rice-mushroom rotation significantly enhanced soil nutrient status, increasing soil organic carbon, available potassium, total phosphorus and total nitrogen. Relationships between soil properties and community composition indicated that rotation-induced changes in the soil environment were linked to these community shifts. Guided by these patterns, we isolated candidate plant growth-promoting fungi from rice–mushroom rotation soils, assembled synthetic consortia and tested their effects in pots, where they consistently enhanced rice growth. Together, these results show that rice-mushroom rotation improves soil fertility and enriches beneficial fungal groups, and that these microbially mediated changes contribute to the yield advantage of rice-mushroom over rice-wheat rotation.

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# Rice root iron plaque as a mediator to enhance biological nitrogen fixation in paddy soil

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## ABSTRACT

Paddy fields have been known to provide a steady supply of N to maintain rice growth even without application of chemical N-fertilizer for several years. Biological nitrogen fixation (BNF) which was considered as the primarily nitrogen supply for rice growth has lately been linked to Fe(III) reduction in paddy field. Rice root iron plaque (IP) is crucial in rhizosphere elements cycling and retaining pollutants, but the synergistic interaction between rhizospheric Fe cycle and BNF remains elusive. Herein, rice seedlings with and without IP on rice root were cultured under hydrophonic conditions to explore the extent and the underlying mechanism of IP influencing BNF using acetylene reduction assay and $^{15}N$ labeling DNA-based stable isotope probing (DNA-SIP) combined with metagenomics. IP on rice root surface exhibited a diurnal Fe(III)/Fe(II) redox rhythm. The decreasing proportion of $Fe_2O_3$ and $Fe^{2+}$ on rice root and the increasing proportion of $Fe_3O_4$ and FeOOH revealed a phase transformation of IP during rice cultivation. In the presence of IP, the *nifH* gene abundance and nitrogenase activity were significantly increased by $1.15\times10^{8}$~$1.15\times10^{11}$ copies/g·dw and 134~566 μmol $C_2H_4$/(L·h), which enhanced the $^{15}N$ abundance in rice shoot and root by 36.4% and 23.1% and further facilitated 2.13 and 1.87 times more biomass accumulation than that without IP. The BNF activity was significantly inhibited by dissociating IP or breaking diurnal Fe redox rhythm. DNA-SIP combining *nifH* gene sequencing revealed that *Azotobacter*, *Clostridium*, *Sporolactobacillus*, *Desulfosporosinus*, *Dechlormonas* and unclassified *Ethanoligenaceae* were involved in assimilating $^{15}N$ in the IP-free rice root. *Azotobacter, Burkholderia, Phytobacter* and *Dechlormonas* were recruited by rice root IP to incorporate $^{15}N$ into biomass. Metagenomic binning identified the presence of genes related to BNF and extracellular electron transfer in such diazotrophs recruited by IP, suggesting their genetic potential to mediate synergetic BNF and Fe(III) reduction. The synergistic interaction between nitrogen fixation and Fe redox cycling on rice root shed light on the overlooked yet significantly crucial contribution of Fe(III)-reducing diazotrophs during rice production. Therefore, stimulating iron plaque formation, accelerating rhizopheric Fe(III)/Fe(II) transformation and enhancing the abundance of Fe cycling related diazotrophs might be feasible strategies to promote biological nitrogen fixation, which are needed to further evaluate in field scale.

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# Assessing Human Land Use Impacts on Soil Properties and Genesis in the Great Plains Region of the United States

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**ABSTRACT**

Humans are accelerating soil change beyond natural rates. Some of these changes enhance soil properties, while others drive degradation, impacting ecosystem health and agricultural productivity. Using legacy soil survey descriptions from the 1950s-1980s in the Great Plains Region of the United States, we are resampling these soils 40-80 years later to quantify changes that have occurred over time. Rather than using the soil surface as a References depth, which is an unstable feature subject to erosion and deposition, we will measure changes in soil thickness using more stable features in the soil, such as depth to bedrock, gravels, or texture contrasts that are unlikely to shift within 100-200 years. Preliminary results show that even with native grassland vegetation at a low-slope (3%) rangeland site, about 10cm of erosion has occurred since 1968. In a floodplain soil, an increase in soluble salts was observed, potentially due to incision of the nearby river that lowered the groundwater table and caused salt precipitation such as gypsum. Such processes may hinder future agricultural productivity in affected areas.

We will expand comparisons across depositional and erosional sites in Kansas, Nebraska, and the Dakotas to determine changes in soil properties such as soil depth, structure, and pH. This study demonstrates the value of legacy soil datasets for detecting short-term anthropogenic soil change and provides insights into how human activities have reshaped Great Plains soils over recent decades.

# Multitemporal Mapping of Soil Degradation to Support Environmental Restoration and Land-Use Planning in Minas Gerais, Brazil

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**ABSTRACT**

The restoration of degraded areas requires accurate diagnostics of soil degradation dynamics and their relationship with land-use and land-cover changes. In Minas Gerais, Brazil, the expansion and intensification of agricultural and livestock activities have accelerated processes such as loss of soil fertility, increased bare soil, and reduced ecosystem services. This study proposes a multitemporal mapping approach to identify and prioritize degraded areas, supporting public policies for environmental restoration and land-use planning.

A temporal dataset from 2018 to 2024 was analyzed by integrating vegetation spectral indices (Normalized Difference Vegetation Index -NDVI, Soil-Adjusted Vegetation Index -SAVI, and Enhanced Vegetation Index - EVI), land surface temperature, and bare soil indicators, which are sensitive to changes in vegetation cover and soil functionality. Data from dry and rainy seasons were evaluated separately with specific weightings to capture seasonal patterns associated with degradation processes. The Analytical Hierarchy Process (AHP) was applied to integrate the variables and generate priority maps for environmental restoration.

The results identified areas with high temporal variation in spectral indices, reflecting reduced vegetation cover, productivity losses, and increased soil exposure—patterns associated with land-use change and environmental degradation. The findings demonstrate the potential of multitemporal remote sensing to identify degradation hotspots and improve decision-making at the territorial scale. The proposed methodology effectively integrates technical and environmental criteria, providing strategic support for sustainable land management, restoration planning, and environmental policy development in Minas Gerais.

**Keywords:** Land use; Soil degradation; Remote sensing; Environmental restoration; AHP.

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# Exploring the environmental feasibility of montmorillonite integration in the electrochemical oxidation of acid mine drainage

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## ABSTRACT

With the escalating global demand for mineral resources, acid mine drainage (AMD) has emerged as a critical environmental concern due to its acidity and heavy metal contamination. To tackle this challenge, this study investigated the integration of montmorillonite (MMT) with electrochemical oxidation pretreatment for AMD, to enhance the removal efficiencies of iron and sulfate, thereby improving the effectiveness of subsequent limestone neutralization. Based on the results of this study, the optimal reaction parameters were determined to be a 5 V electrolysis voltage under heating and static conditions. Incorporating MMT into the electrochemical system significantly enhanced Fe(II) oxidation and sulfate removal, resulting in total Fe and sulfate removal rates of 84.9% and 12.01%, respectively, which were attributed to MMT's adsorption capacity, ion exchange properties, and co-precipitation mechanisms driven by Fe(III) hydroxide formation. Comprehensive characterization using scanning electron microscopy, X-ray diffractometry, Fourier-transform infrared spectroscopy and X-ray photoelectron spectroscopy analyses confirmed the presence of schwertmannite and FeO(OH) in the precipitates, highlighting the increased specific surface area, micropore volume, and structural integrity of MMT. Adsorption experiments demonstrated superior arsenic (As(III)) adsorption efficiencies in precipitates formed through electrochemical oxidation with MMT incorporation, supported by pseudo-second-order kinetic modeling, indicating that MMT had been modified through Fe(III) intercalation. Additionally, the integration of MMT reduced neutralizing agent consumption by up to 68.1%, contributing to a substantial decrease in overall treatment costs. In conclusion, the findings underscore the synergistic interplay between MMT and electrochemical oxidation, presenting a sustainable and economically viable solution for AMD remediation. This integrated approach not only enhances pollutant removal efficiency but also generates environmentally valuable by-products with superior adsorption capabilities.

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# Methane Mitigation and Arsenic Immobilization in Paddy Soils by Sulfur-Containing Amendments Applied to Stimulate Sulfate-Reducing Bacteria

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**ABSTRACT**

Paddy soils inherently produce methane ($CH_4$) under anaerobic conditions, and when the soil is contaminated with arsenic (As), the reducing environment promotes as the formation of highly mobile and toxic As(III). Sulfate-reducing bacteria (SRB) compete with methanogens for electron donors and supplying sulfate sources can suppress methanogenesis while simultaneously the formation of reduced sulfur species that immobilize As. This study investigated the coupled mechanisms of $CH_4$ reduction and As immobilization in paddy soils treated with sulfur-based amendments, including elemental sulfur, gypsum, and schwertmannite. Ten grams of soil were treated with 0.3% of each amendment, followed by 30 mL of 1000 mg/L As(V) under $N_2$-purged anaerobic conditions, and greenhouse gas emissions, As concentration in solution, and As species were monitored for 250 days. To elucidate the As immobilization mechanisms, adsorption experiment were conducted with 0.1 g of each amendment and 50 mL of 50 mg/L As(III) or As(V) for 48 hours. Elemental sulfur, gypsum, and schwertmannite reduced $CH_4$ in soils by 78.7%, 65.5%, and 88.0%, respectively, while immobilizing As by 11.4%, 8.2%, and 22.3% compared with the unamended control. Unlike the control, where As(V) was reduced to As(III), no reduction occurred in the amendment-treated soils because of alternative electron acceptors (e.g., sulfate) thereby limiting the formation of the more toxic As(III) species. Dehydrogenase activity followed the order schwertmannite > elemental sulfur > gypsum, suggesting that higher As immobilization corresponded to lower As toxicity and increased microbial activity. The immobilization of As(III) and As(V) was probably achieved by complexation with sulfur-based amendments as supported by high resolution-transmission electron microscope (HR-TEM) observations. Overall, sulfur-based amendments particularly schwertmannite simultaneously reduced $CH_4$ emissions and immobilized As through surface-bound mineral formation and microbially mediated sulfate reduction, highlighting their potential for mitigating climate and contamination risks in flooded paddy soils.

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# Reducing the Global Warming Potential of Rice Farming: Why Biochar Works Better than Compost

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**ABSTRACT**

Organic amendments such as biochar and compost are widely regarded as stable carbon inputs that enhance soil carbon sequestration and mitigate greenhouse gas (GHG) emissions in paddy systems. However, current assessments typically focus on in-field emissions, often neglecting the climate burden associated with amendment production processes. Here, we conducted a comprehensive life cycle assessment (LCA) to quantify the net global warming potential (GWP) of applying fresh manure, compost, and biochar (12 Mg $ha^{-1}$ dry weight) in a conventional rice paddy, spanning industrial production to field application. Greenhouse gas fluxes were measured using a closed-chamber method, and soil carbon stock changes were integrated into GWP estimates. Relative to fresh manure, compost application reduced net GWP within the cropping sector by 43%, driven by a 25% decrease in $CH_4$ emissions and a 39% increase in soil carbon. However, composting released an additional 34 Mg $CO_2$-eq to produce 12 Mg of compost, generating a 34% increase in net GWP under a full-system boundary. In contrast, biochar treatment transformed the paddy into a net GHG sink, reducing $CH_4$ emissions by 56% and increasing soil carbon by 13%, while the pyrolysis process generated 19 Mg $CO_2$-eq. Overall, biochar reduced net GWP by 28% compared with fresh manure when considering full system impacts. Grain yield did not differ between compost and biochar, although compost improved yield over fresh manure. Consequently, biochar lowered GHG intensity (net GWP per unit grain yield) by 33%, whereas compost increased it by 22%. Our findings demonstrate that although compost confers agronomic benefits and mitigates in-field emissions, its production-phase climate burden substantially offsets these gains. Biochar emerges as a more sustainable amendment for minimizing the global warming impact of rice cultivation when assessed across the entire system boundary.

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# Cloud-Based Soil Erosion Drivers and Sediment Yield Assessment Using RUSLE–SDR Modeling in a Himalayan Watershed.

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**ABSTRACT**

Soil erosion is a serious sustainability challenge that causes land deterioration, sedimentation in water bodies, and reduced storage capacity in dam reservoirs, causing severe difficulties in transboundary watersheds with limited data availability, like Mangla. Therefore, this study utilized the Revised Universal Soil Loss Equation (RUSLE) integrated with a Sediment Delivery Ratio (SDR) model. Quantifying the spatial distribution of soil loss and sediment yield, identifying the key environmental drivers, and evaluating their response mechanisms for watershed management. Results show the average annual soil loss of 103.90 tons $ha^{-1}$ $yr^{-1}$, with 64.5% of the region exceeding the tolerable erosion rate (> 25 tons $ha^{-1}$ $yr^{-1}$). Sedimentation yield of 20.75 tons $yr^{-1}$ highlighted the severe problem of siltation in Mangla dam, where the key drivers of soil erosion include topographic factor, where steep slopes increase runoff velocity and erosion potential, cover management factor, where the weak vegetation allows high soil exposure and soil detachment. This cause-and-effect relationship highlights how topography and land cover conditions influence erosion severity. Global and local Moran's I index analysis also confirmed that soil erosion risk exhibits significant spatial clustering, with critical hotspots concentrated in the steep and sparsely vegetated sub-basins. Spatially explicit risk maps pinpoint essential zones of the Kunhar, Neelum, and Jhelum Basins for urgent conservation practices. This work demonstrates the effectiveness of cloud-based geospatial modeling for sustainable watershed management in data-scarce regions. These findings support soil conservation practices like terracing and afforestation and provide actionable insights for hydropower security and achieving SDG 15 (Life on Land).

**Keywords:** Soil erosion modelling, Sediment yield estimation, Soil erosion drivers, Spatial autocorrelation (Moran's I), Google Earth Engine (GEE).

# Changes in farm business model: Combined effects on soil health, ecosystem services, farm profit, and associated needs for incentives

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**ABSTRACT**

Growing demand to improve soil health and ecosystem services calls for alternative farm business models. Yet such transitions remain challenging because they involve synergies and trade-offs between soil health, ecosystem services, and farm profit. Although these interactions have been conceptually explored (Wang-Touri et al., 2025), few studies assess them holistically in real farm contexts. This research presents a diverse set of alternative business models and evaluates their implications for soil health, ecosystem services, farm profit, and associated needs for incentives.

Through an iterative participatory process, we co-designed alternative business models with six European farms. Each alternative was assessed ex-ante using partial budgeting (Kay et al., 2012) and a structured expert elicitation (IDEA protocol)(Hemming et al., 2018) to evaluate impacts on soil health, ten ecosystem services, and farm profit. Farmers then reflected on the outcomes in semi-structured interviews, discussing their willingness to adopt each option and how stakeholders and policies might influence adoption.

Across the six case studies, seventeen alternatives of varying complexity were identified, including changes to fertilizer strategies, reduced tillage, modified cropping plans, and alley-cropping (agroforestry). Results show distinct synergies and trade-offs across soil health, ecosystem services, and farm profit, with several offering triple gains. More complex changes produced greater improvements in soil health and ecosystem services, while not necessarily creating trade-offs with profit—yet they rarely delivered strong economic gains. Thus, the options with the highest ecological benefits were not the most economically attractive.

These findings lead to two main contributions. First, while additional incentives are not always essential for adoption, supportive measures—financial incentives, training, advisory services, regulatory simplification, and citizen engagement—can enhance uptake. Second, the structured approach developed here offers a novel and transferable method for jointly assessing soil health, ecosystem services, and farm profit, helping identify promising pathways toward more sustainable, resilient, and economically viable farm business models.

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# Effect of autumn ratoon biomass on the rice growth and biomass during the following summer season under organic cultivation

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## ABSTRACT

**Background:** Ratoon rice regenerates as a second crop from stubble left after harvesting the main crop. In northeast Japan, it rarely reaches maturity due to low temperature during autumn and winter seasons. However, autumn ratoon biomass, as similar as rice straw, can supply carbon (C) and nitrogen (N), potentially influencing the rice growth in following summer season and soil C and N dynamics, while contributing C to methane ($CH_4$) emissions and N as a natural fertilizer under organic cultivation.

**Objectives:** This study evaluated the effects of ratoon rice growth over autumn and winter seasons on subsequent summer rice growth.

**Materials and Methods:** The experiment was conducted at Yamagata University Farm using ratoon plants collected after the 2024 harvest season by cylindrical column. Then twenty plants were transplanted into the pots (⌀ 27.0 × h19.5 cm) and assigned to four treatments combining two temperature conditions (ambient outdoor and glasshouse) and light availability: Glasshouse with Light (GHWL), Glasshouse no Light (GHNL), which the pots were covered by black sheet to shade sunlight, Outdoor with Light (ODWL), and Outdoor no Light (ODNL). After winter, all pots were plowed and rice seedlings were cultivated in outdoors under uniform conditions during the 2025 summer. Rice growth parameters and final biomass were measured at maturity. **Results:** As the results, there were no difference of stubble biomass after autumn and winter seasons among 4 treatments, however, the new ratoon shoot biomass was varied significantly. Compared with no light condition, the ratoon rice biomass were increased with light condition at 65% and 28% for glasshouse and natural outdoor conditions, respectively. The ratoon rice growth during the autumn and winter effected summer rice growth. The total biomass were 44.7, 35.7, 29.9 and 22.38 g/pot for GHWL, ODWL, GHNL and ODNL treatments, respectively.

**Conclusion:** These results demonstrate that autumn and winter management strongly influences subsequent rice performance. Higher temperature in glasshouse condition and light availability during off-rice growth season not only directly affected ratoon rice growth, but also indirectly influenced subsequent rice growth and yield under organic cultivation.

# Effects of fertilizers on arsenic accumulation in ratoon rice: implications for human health risks

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**ABSTRACT**

Ratoon rice cultivation has received increasing attention in recent years due to its potential to reduce the inputs of labor, seeds, and energy. However, ratoon rice often requires fertilizer supplementation due to its generally lower yield. Furthermore, recent studies have indicated that ratoon rice can effectively reduce the arsenic (As) concentration in rice grain. Therefore, a pot experiment was conducted in the present study to investigate the effect of different fertilizer amendments on As accumulation in ratoon rice with three common Taiwanese rice cultivars—TCS17, TK9, and TK16—as experimental materials. Additionally, the interaction of fertilizer treatments and cultivars with As and iron in the root plaque was evaluated, and the human health risk associated with consuming ratoon rice was assessed. Results showed a significant difference in the effect of rice husk amendment among the three rice cultivars, with TCS17 showing a significant reduction in As uptake. This highlights that different fertilizer amendment strategies must be adopted for different rice cultivars to effectively reduce As accumulation in ratoon rice. Furthermore, fertilizer amendment treatments also significantly affected the concentration of As chelated in the iron plaque. The three rice cultivars showed significant differences in the index As sequestration by Fe oxides in root plaque (IAS), and across all cultivars and treatments, IAS exhibited a significant negative correlation with brown rice As concentration. This suggests that managing IAS is a feasible approach to reduce As concentration in ratoon rice grains. Health risk assessment results further indicated that organic fertilizer and rice husk were effective in reducing the health risk of TCS17, whereas the non-carcinogenic and carcinogenic risks of TK9 and TK16 exceeded the acceptable range under all treatments. Overall, this study clarified the influence of fertilizer and cultivar differences on As accumulation in ratoon rice, highlighting the importance of selecting appropriate cultivars combined with reasonable fertilization strategies to mitigate As accumulation in ratoon rice and its associated health risks.

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# Managing water and litter inputs to safeguard wetland soil health: coupled C-N-P responses to drying-rewetting in River Murray floodplain soils

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## ABSTRACT

Hydrological volatility is increasing in many river-floodplain wetlands, intensifying drying-rewetting (DRW) transitions that can reshape "soil health" through coupled redox, organic-matter and nutrient feedback (Kingsford, 2011; Zhang and Furman, 2021). Although Birch-type rewetting pulses are well established for upland soils (Fierer and Schimel, 2002; Lopez-Sangil et al., 2018), wetland responses can diverge and depend strongly on litter quality and hydrologic history (Gao et al., 2020).

We synthesize three River Murray soil-column studies testing factorial combinations of water regime (continuous submergence vs DRW) and litter identity to quantify coupled C-N-P outcomes relevant to soil health and downstream water quality. We measured pore- and overlying-water nutrients, soil microbial biomass pools, DOC quantity and UV-Vis indices, FTIR organic-matter signatures, and $CO_2$/$CH_4$ fluxes. Natural-abundance $\delta^{13}C$ of $CO_2$ was used to apportion litter- vs. soil-derived respiration.

Across studies, litter chemistry set the mobilization "ceiling": labile litters (willow and *Themeda*) generated larger DOC and dissolved nutrient pulses, whereas lignin/phenolic-rich red gum constrained short-term mineralization and shifted DOC optical signatures (Moorhead and Sinsabaugh, 2006; Kennedy and El-Sabaawi, 2017). Water regime primarily governed timing and partitioning. DRW consistently suppressed methanogenesis during rewetting and shifted gaseous C towards $CO_2$, consistent with delayed re-establishment of strongly reducing conditions and altered electron-acceptor availability (Knorr and Blodau, 2009; Yarwood, 2018). DRW also amplified short-lived inorganic-N pulses and altered DON trajectories, with elevated eutrophication potential when labile willow inputs were present (Harris et al., 2021). For P, invasive willow increased dissolved P and soil microbial P relative to red gum, while DRW mainly re-timed peaks and strengthened non-additive responses among P fractions (Paranaíba et al., 2020; Skinner, 2022).

Overall, these studies show that "managing water for soil health" requires co-management of hydrology and species-specific litter inputs: DRW governs redox routing and nutrient timing, while litter quality controls the magnitude and composition of mobilised substrates that drive greenhouse-gas balances and episodic DOC export under flooding (Gibbs et al 2022)

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# Evaluating Cross-Regional Models for Predicting Soil Carbon and Properties in Taiwan Using Mid-Infrared Spectroscopy and Machine Learning

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**ABSTRACT**

Mid-infrared spectroscopy (MIR, 4000-650 $cm^{-1}$) offers rapid, non-destructive, and low-cost analysis of multiple soil properties, making it attractive for long-term soil carbon monitoring and MRV (Monitoring, Reporting, and Verification) frameworks. However, its predictive performance may vary across regions with heterogeneous soil environments. This study integrated 2,780 MIR spectra from a nationwide paddy soil database (TARI, n=1912) and two small-scale sites in Changhua Beidou (MDU, n=468) and Kaohsiung Qishan (QIN, n=400). Soil samples from 0-10 and 10-30 cm were analyzed for MIR spectra and laboratory-measured total organic carbon (TOC), pH, and cation exchange capacity (CEC). A subset of TARI samples was further fractionated to obtain mineral-associated organic carbon (MAOC) and particulate organic carbon (POC). Spectra were corrected using baseline correction, smoothing, and SNV, followed by calibration-validation splitting (70/30) and model development using Partial Least Squares (PLS), Cubist, and Random Forest. Principal component analysis (PCA) was applied to assess spectral variability among regions.

TOC calibration accuracies were consistently high ($R^2$=0.89-0.97), while validation performance differed by region. MDU, with a narrow TOC range (0.39-3.11%), showed moderate transferability ($R^2$=0.64-0.80). QIN, characterized by a wide TOC range (0.15-5.37%), yielded superior predictive performance (validation $R^2$=0.86-0.92). TARI exhibited moderate validation accuracy ($R^2$=0.74-0.77) due to strong cross-regional heterogeneity. Underestimation in TOC <0.4% and >4% occurred across all models, reflecting limited sample representation at these extremes. CEC predictions were robust across regions ($R^2$=0.79-0.93), while pH predictions were inconsistent ($R^2$=0.41-0.82) due to narrow pH variation in MDU and QIN. For SOC fractions, MAOC was best predicted by Cubist+SNV ($R^2$=0.86), whereas POC, with higher heterogeneity, was best predicted by Random Forest ($R^2$=0.85).

PCA revealed that spectral variation was governed mainly by sampling region rather than soil order or TOC concentration. Clear clustering of TARI, MDU, and QIN samples indicated strong regional spectral signatures consistent with model performance patterns, emphasizing the influence of geographic heterogeneity on MIR-based predictions.

Overall, MIR demonstrated strong capability for predicting TOC, CEC, MAOC, and POC; however, model generalization depended heavily on regional data structure. Cubist showed the best cross-site performance, PLS was more stable for homogeneous datasets, and Random Forest excelled for highly heterogeneous targets. Establishing a nationwide MIR spectral library, combined with local calibration and expanded sampling in TOC extremes, will improve cross-regional applicability of MIR-based prediction models for carbon monitoring and MRV applications.

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# Integrated remediation strategies by health risk assessment of brown rice approaching technology for As, Cd, Cr, Ni, Cu and Zn-contaminated paddy soils in Taiwan

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**ABSTRACT**

Soil quality (or soil health) is defined as the capacity of paddy soil ecosystems to sustain their biological, chemical, and physical functions. The Soil Quality Index (SQI) has been widely adopted as an integrative tool to quantify the combined effects of multiple soil properties on overall soil quality, particularly for assessing the productivity and health risks of contaminated soils. However, studies that systematically evaluate changes in soil quality following contamination or remediation remain limited. This study assessed variations in soil quality and associated health risk-based assessment (HRA) in Taiwan paddy fields exposed to diverse sources of heavy metal contamination, including illegal industrial wastewater discharge, arsenic-rich irrigation water, industrial-derived metal inputs, and geogenic enrichment from serpentine parent materials. Conventional remediation practices in contaminated paddy soils in Taiwan commonly rely on dilution or soil replacement to meet single regulatory thresholds (e.g., As 60, Cd 3, Cu 200, Cr 250, Ni 200, Zn 600 mg/kg). Although these approaches enable rapid regulatory compliance, they often alter inherent soil properties and negatively affect rice cultivar performance. Therefore, slightly contaminated soils should be regarded as sustainable agricultural natural resources, and remediation strategies should prioritize ecological function, agricultural productivity, and food safety. Establishing a health risk-based assessment framework to guide appropriate remediation technologies and soil management is both pragmatic and innovative. For example, approximately 300 ha of arsenic-enriched (100–500 mg/kg) volcanic paddy soils in northern Taiwan and around 500 ha of irrigation-affected farmland in southern Taiwan exhibit elevated total soil arsenic concentrations, yet inorganic arsenic levels in brown rice remain below 0.3 mg/kg, indicating negligible health risk. In cadmium-contaminated areas near industrial zones (limit: 0.4 mg/kg), the key factors controlling Cd accumulation include soil pH, total Cd concentration, and rice cultivar, with indica varieties posing higher risks than japonica varieties. A health risk-based cultivar selection system was therefore developed to mitigate exposure. Likewise, paddy soils derived from serpentine parent materials in eastern Taiwan naturally contain high levels of chromium and nickel (500–1000 mg/kg); however, their low bioavailability results in minimal metal accumulation in brown rice, and health risk assessments reveal no significant concern, suggesting that soil remediation is unnecessary. For soils with moderately elevated copper and zinc concentrations (300–800 mg/kg), given that metal levels in rice remain within safe dietary intake limits, the use of low-cost soil amendments for in situ dilution and stabilization, combined with comprehensive health risk assessment and adaptive soil management, is recommended. Overall, sustainable utilization of contaminated paddy soils can be achieved through science-based risk communication, targeted remediation interventions, and adaptive soil management that balances environmental quality with agricultural productivity.

**Key Words:** paddy soil, brown rice, heavy metal pollution, health risk-based assessment, soil remediation.

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# Effects of broiler litter and inorganic nitrogen on soil chemical indicators under varying row spacings in rainfed, no-till cotton systems

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**ABSTRACT**

Broiler litter is commonly utilized in cropping systems in the Southeastern United States; however, its effects on soil nutrient indicators under different row spacings in rainfed, no-till systems remain insufficiently characterized. From 2006 to 2009, a field experiment was conducted at the Pontotoc Ridge–Flatwoods Branch Experiment Station (Pontotoc County, Mississippi) on an Atwood silt loam (Typic Paleudalf) within a humid subtropical climate. The study employed a randomized complete block design with a split-plot arrangement, where row spacing (7.5, 15, and 40 inches) served as main plots and fertility management as subplots. Fertility treatments included an unfertilized control, inorganic nitrogen fertilizer (120 lb N $ac^{-1}$ as ammonium nitrate), and broiler litter applied annually at rates of 2, 4, and 6 tons $ac^{-1}$. Phosphorus and potassium were applied in the first year based on soil test recommendations. All plots were managed under rainfed, no-till conditions with standard weed and pest control practices. Broiler litter nutrient concentrations were determined at each application to quantify nutrient inputs. Soil pH, total carbon, total nitrogen, mineral nitrogen ($NO_3^-$ and $NH_4^+$), water-extractable phosphorus, and Mehlich-3–extractable macro- and micronutrients were measured from 2006 to 2009. The main and interactive effects of row spacing and fertility management will be evaluated across years. These results are expected to inform nutrient management strategies for broiler litter application in rainfed, no-till cotton systems in the Southeastern United States.

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# Rye–clover cover crop configuration (random vs alternating rows) with poultry litter: soil chemistry and cotton yield in Mississippi

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**ABSTRACT**

Cereal rye (Secale cereale) and crimson clover (Trifolium incarnatum) are frequently recommended for mixed cover cropping; however, cereal rye often dominates when seeds are combined and planted as a random mixture, resulting in inconsistent achievement of the intended stand proportion. This study investigates whether an alternative planting configuration, specifically alternating drill rows of rye and clover, leads to different soil and cotton responses compared to a conventional random mixture, and whether these responses interact with poultry litter inputs in Mississippi (Southeastern U.S.). A two-year small-plot field experiment (12 ft × 40 ft) was implemented using a randomized complete block design with a split-plot arrangement and four replicates. Poultry litter (0 versus 2 tons per acre, applied prior to cover crop planting) was assigned to main plots. Subplots consisted of five treatments: winter fallow (no cover crop), cereal rye alone, crimson clover alone, a random rye–clover mixture, and an alternating-row rye–clover configuration (three rows of clover followed by two rows of rye), established by drilling at 7-inch row spacing. Cover crops were planted in mid-October and terminated two to three weeks before planting cotton as the main crop. Measurements included soil indicators at 0–15 cm (2020–2021), cotton yield (2020–2021), and crop nutrient uptake (2021), supported by baseline soil characterization (2019). Split-plot mixed models and planned contrasts will be used to quantify the effects of cover crop configuration and poultry litter on soil nutrient indicators and cotton performance, thereby informing mixture recommendations for rainfed systems.

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# Triangular approach (SQ-GQ-GY) based soil health assessment - A novel mechanism for ranking Resilient Rice Ecologies of eastern India

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**ABSTRACT**

Soil quality, either known as "capacity of a soil to function" or "fitness for use" has become an increasingly demanding concept to realize soil's potentiality for both cultivation and environmental management perspectives. Since the last two decades, enumeration of SQI (soil quality index) has dominated by Soil Management Assessment Framework model, with three 3-I's pillars: Identification, Interpretation and Integration of crucial soil quality indicators. However, soil health researchers, especially under rice-growing agroecology, have perceived the important relationship of the developed SQI with other components- grain yield and grain quality, and sometimes with GHG emissions. Summarizing a three-years' study, soil indicators were interconnected under specific soil functions viz. *Nutrients cycling*, *Resistance and Resilience*, *Biodiversity and habitat*, majorly converging soil C, nutrients and microbial indicators to integrate SQI. C-related indices viz., carbon pool, lability index and Carbon management index derived from total organic carbon (TOC) and different C-fractions, revealed that higher values of Carbon pool index (CPI) were expressed by irrigated organic lowland of Cuttack (1.14-1.74%) and upland soils of Hazaribagh (1.09-1.94%) over others; while Carbon management index (CMI) showed an order of: Irrigated organic lowland soil > Upland irrigated soil > Upland rainfed soil > Saline soil. Among soil biological parameters, saline soil of coastal region exhibited lower enzymatic activities compared to other rice ecologies. Irrigated lowland soil showed comparatively higher soil enzymatic activities and microbial biomass N, P, than upland soils. Further, a greater range of AWCD, Shannon and McIntosh Index representing total microbial community and functional diversity indices analysed using Biolog® eco microplates disclosed that irrigated lowland rice soil under organic management had higher richness and evenness of soil microbes in than other rice ecologies. Our findings showed that developed SQI and screened soil indicators is dependent on both crop yield and grain quality parameters in four diverse ecologies of rice-based system belong to eastern India. PCA-based MDS indicators were variable across studied ecologies: TOC, pH, av. N, $C_{min}$, MBC, MBN (long-term organic-fertilized soil), av. P, K, Zn, $C_{min}$, MBP, soil enzymes (upland rainfed and upland irrigated), SOC, EC, av. N, soil enzymes and MBC (coastal rice ecology). Rice grain quality parameters (protein & amylose contents, Fe and Zn) showed association with both SQI and soil indicators, and hence SQ also acted as grain quality predictors. Variable relationships (SQ-GQ-GY) established in different ecologies; more the SQI (>0.70-0.75) a perfect triangular relationship explained.

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# Biochar application improves soil health and tomato growth under drip irrigation in acidic soil

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**ABSTRACT**

Excessive application of chemical fertilizers has led to increasingly serious problems of soil acidification and crop growth obstacles. The localized irrigation characteristics of drip irrigation result in the concentration of soil moisture and nutrients, thus affecting soil physicochemical properties. This alteration of soil properties may cause spatially uneven distribution of soil acidification, thereby hindering its remediation. Biochar application can improve soil acidification, but the regulatory mechanisms of biochar on soil acidification characteristics and crop growth under drip irrigation conditions are currently unclear. This experiment set up different biochar application treatments under drip irrigation conditions to study the distribution patterns of uneven soil acidification; it also explored the effects of different biochar application rates on uneven soil acidification under drip irrigation conditions, and its influence on crop growth and water use efficiency. The results can provide a References for soil acidification improvement and the development of water-saving agriculture.

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# Enhancing soil health through organic amendments in an acid soil

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**ABSTRACT**

Long-term excessive application of chemical fertilizers is one of the main factors leading to soil acidification. Studies show that soil acidification extensively affects soil health through disrupting soil structure, causing nutrient imbalances, and reducing microbial activity. Organic amendments are of great importance to improve soil health and plant growth. Different organic amendment treatments under two distinct deficit irrigation regimes were used to remediate an acid soil caused by excessive use of chemical fertilizers. We measured soil pH, organic carbon fraction, aggregate composition, moisture retention, microbiome structure and plant root development, photosynthetic rates, water use efficiency. This work emphasizes the capacity of lignin-based organic amendments to alleviate acidic soil health and sustain wheat productivity under limited water.

# The Potential of Returning Lignified Sesbania and Sun Hemp to the Soil to Increase Soil Organic Matter in Tropical Farmlands

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**ABSTRACT**

Cultivation of sesbania and sun hemp provides nutrients for subsequent crops; however, their potential to enhance soil carbon sequestration remains uncertain. Unlike previous practices where green manure was incorporated into the soil during its tender stage, this study allowed the plants to mature before being returned to the field. In the first year, experimental fields comprising paddy, upland, and paddy-upland rotation systems were established at the National Pingtung University of Science and Technology. During the second cropping season, Sesbania, sun hemp, and naturally occurring weeds were cultivated for over 10 weeks before incorporation. The results showed that, in paddy fields, rotation with Sesbania or sun hemp resulted in 4.6 and 3.6 t/ha of carbon input more than weeds. Using a decomposition rate of 70% over one year, the estimated increase in carbon sequestration potential was 1.38 and 1.08 t C/ha, respectively. In upland fields, sun hemp incorporation after the cropping season added 2.1 t C/ha more than weeds, with an estimated annual increase of 0.63 t C/ha. Measurements of soil carbon stocks within 30 or 50 cm depths over two years show no significant differences among baseline values, pre-green manure levels, post-green manure incorporation levels, or treatments. It is recommended that the pre-green manure planting timepoint serve as the baseline for monitoring. A linear regression analysis of soil carbon stock changes over two years revealed that, despite high variability leading to insignificant regression and determination coefficients, Sesbania and sun hemp demonstrated higher sequestration rates compared to weeds. The rates were 7.2 and 10.3 t C/ha/30 cm/year, respectively, aligning with trends observed in some international studies. In laboratory incubation tests, early carbon release following green manure incorporation primarily originated from inherent soil organic carbon, with minimal influence from different green manure. This outcome is likely because the green manure had not yet transformed into soil organic carbon, and the carbon input from a single application was insufficient. In the second year, upland fields were cultivated again. For the first cropping season, maize grown under the three treatments exhibited no significant differences in growth vigor, ear length, or yield, indicating that no production-reduction effects occurred. Consecutive typhoons during the second year hindered the growth of sesbania and sun hemp, although sesbania produced more biomass, contributing approximately 0.6 t C/ha more carbon to the soil than weeds.

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# Optimizing Water-saving Irrigation Strategies: Integrative Assessment of Soil Quality, Crop Yield, Greenhouse Gas Emissions, and Microbial Ecology in Rice Paddies

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## ABSTRACT

Conventional rice cultivation systems are extremely water-intensive, requiring 2-3 times more water than other cereal crops (Barker et al., 1999). With rising water scarcity caused by climate change, pollution, and competition from urban and industrial sectors, irrigation sustainability is under increasing threat, jeopardizing food security (Fan et al., 2012). In parallel, paddy fields are major sources of anthropogenic GHG emissions, particularly methane, which is generated in anaerobic conditions and accounts for 5–20% of global $CH_4$ emissions and nearly half of agriculture's total GHGs (IPCC, 2014; Carlson et al., 2017). Water-saving irrigation is a promising strategy to enhance food security and reduce greenhouse gas (GHG) emissions. However, few studies have tested multiple irrigation intensities in a single field experiment, limiting direct comparisons of their agronomic and environmental effects. This study compared continuous flooding with two water-saving methods. Its key innovation lies in a comprehensive, field-scale assessment of impacts on soil quality, crop yield, GHG emissions, and microbial ecology—offering an integrated perspective lacking in prior research. Results showed that Alternate Wetting and Drying (AWD), following International Rice Research Institute guidelines, reduced water use by 23% without affecting yield. Periodic irrigation (PI), applied every nine days, saved 60% more water but caused a 19% yield loss. While CH4 emissions declined under reduced irrigation, increased $N_2O$ emissions offset this benefit, leading to no net reduction in global warming potential. Overall, different irrigation methods had no significant effect on the Soil Quality Index. However, the results indicate that water-saving irrigation may increase microbial physiological stress and alter microbial communities even in the short term. Therefore, this study recommends monitoring changes in soil microbial communities in areas under long-term water-saving irrigation, particularly in regions with higher degrees of water reduction, to ensure soil quality.

**Acknowledgments**

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# Changes in soil microbial community structure and carbon, nitrogen and sulfur functional genes under different cultivated land use patterns

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**ABSTRACT**

Soil microorganisms participate in almost all soil ecological processes and are crucial for maintaining ecosystem functions and terrestrial carbon, nitrogen, and sulfur cycles. Land use patterns significantly affects bacterial communities and their mediated biogeochemical processes by altering the soil microenvironment. However, further research is needed on how bacterial community structure, co-occurrence networks, and functional genes are coupled in response to different crop planting patterns. This study systematically analyzed the characteristics, network topology, and differences in C, N, and S cycle functional genes and their driving mechanisms in soil bacterial communities under four land use patterns (rice, wheat, maize, and soybean). The results showed that land use pattern significantly altered the relative abundance of dominant bacterial taxa. Functional gene analysis revealed that different land use patterns significantly altered the abundance distribution of C, N, and S cycle functional genes. This study reveals how crop planting patterns drive the reorganization of microbial metabolic potential by altering soil physicochemical properties, providing a References for sustainable nutrient management in agricultural ecosystems.

# Modified biochar enhances the growth of pepper and reduces the accumulation of cadmium in soil contaminated with cadmium

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**ABSTRACT**

To address the severe challenge of Cd pollution in agricultural ecosystems, this study developed a novel magnetically modified biochar (MFBC) based on coconut shell waste. Modification significantly increased the specific surface area (496.82 $m^2 \cdot g^{-1}$) and oxygen-containing functional groups on the surface of the biochar. Application of MFBC effectively promoted the transformation of heavy metals in the soil from a weakly acidic extractable state to a residual state. Under the regulation of MFBC, the bioavailability of Cd in the soil was significantly reduced, while simultaneously increasing soil cation exchange capacity and organic matter levels (23.69%–35.40%), significantly improving soil fertility. Pot experiments confirmed that MFBC, by mitigating oxidative stress, increased the root length of bell peppers by 31.56%–39.97% and the photosynthetic rate by 24.10%–54.70%. Simultaneously, MFBC significantly blocked Cd translocation within the plant, substantially reduced Cd accumulation in the fruit, and improved quality indicators such as vitamin C and soluble sugars.

# Organic amendments affect soil organic carbon and water-salt transport under subsurface drainage in a coastal reclamation area

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**ABSTRACT**

As an important reserve of arable land, the development and utilization of saline-alkali land in coastal reclamation areas is of great significance to ensuring food security. Applying soil amendments is an effective way to promote the transformation of coastal saline-alkali land into agricultural soil. However, under high salinity and high pH conditions, the process by which soil amendments drive the accumulation of soil organic carbon and water-salt transport in coastal reclamation areas under subsurface drainage systems remains unclear. This study set up five soil amendment treatments on the saline-alkali farmland under subsurface drainage in the coastal reclamation area of Jiangsu Province, China. We studied the effect of different treatments on the increase of soil organic carbon, as well as the distribution and content of organic carbon in soil aggregates of different particle sizes; analyzed the characteristics of soil water-salt transport. The results can provide a References for the application of soil amendments in saline-alkali soils in coastal reclamation areas.

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# Effects of subsurface drainage spacing and organic fertilizer application on water and salt transport characteristics of saline–alkali soil

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**ABSTRACT**

The underutilization of saline-alkali land is a long-standing problem affecting agricultural production. While subsurface drainage is an effective salt removal technology, long-term use can lead to soil nutrient loss, soil compaction, and reduced soil productivity. Therefore, the improvement of coastal saline-alkali land should consider multiple factors, including desalination and fertilization, to establish a beneficial water-salt synergistic ecological environment. This study set up three subsurface drainage spacings and three organic fertilizer application rates, conducting a field experiment on saline-alkali farmland in the Tiaozini reclamation area of coastal China. The study investigated the temporal processes of soil water and salt transport and the patterns of soil salt leaching/accumulation; it also analyzed the response characteristics of soil physical moisture properties (soil bulk density, soil pore structure, soil water holding capacity, soil aggregate stability, and soil infiltration rate). The results can reveal the regulatory mechanism of soil fertilization and subsurface drainage synergistically on soil water and salt transport and crop growth, providing a References for improving the quality of coastal saline-alkali soil.

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# Microbiome-enabled biochar tightens nitrogen cycling and boosts wheat water productivity under regulated deficit irrigation

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## ABSTRACT

Water scarcity starts to restrict the production of wheat, leading to deficit irrigation, which will help save water but may increase the effects of oxidative stress and nitrogen loss, compromising the stability of yield. In this case, biochar-based microbial fertilizer is considered for evaluation as one of the rhizosphere-engineering interventions to save nitrogen and enhance water productivity in regulated deficit irrigation. Controlled 4×4 factorial pot experiment, and combined measurements of soil carbon fractions, inorganic N speciation, enzyme activity, microbial community structure, and wheat physiology and yield formation. As a result, in various irrational states, BMF enhanced the status of soils in terms of carbon and availability of K, and moderately affected soil pH by +0.26, which was evidence of better buffering and nutrient solubility. Microbial ordination showed that there was significant community reassembly when using BMF. Similarly, since it is paramount, BMF found tighter N cycling and lower nitrification pressure changes, where it directed the inorganic nitrogen to increased $NH_4^+$ and decreased $NO_2^-$/$NO_3^+$. The most consistent gains, agronomically, were observed under a moderate × moderate regime of high water-use efficiency of whole-plant grain mass (~18 %) relative to the unamended control of the same moisture status. Generally speaking, deficit irrigation controlled by microbiomes and biochar co-optimization can be considered a climate-intelligent and scalable strategy to achieve water-limiting wheat systems with optimized water application, nitrogen charging, and a stable output in water-constrained environments.

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# Soil ridging combined with soil amendments regulates the arsenic-cadmium related geochemical cycles and mitigate its accumulation in rice

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**ABSTRACT**

Co-contamination of arsenic (As) and cadmium (Cd) in paddy soils poses a serious global threat to rice food safety due to their high bioaccumulation in rice grains. As a result from their contrasting geochemical behaviors—As being more mobile under anaerobic conditions and Cd under acidic, oxidized conditions—developing an effective, field-applicable strategy to simultaneously reduce their bioavailability in rice cultivation systems remains a critical need. This study aimed to evaluate and mechanistically elucidate the efficacy of an integrated approach combining ridge cultivation with organic (biochar) and inorganic (calcium-magnesium phosphate, CMP) amendments in an acidic paddy field in southern China (pH 5.17; 66.5 $mg \cdot kg^{-1}$ As and 0.41 $mg \cdot kg^{-1}$ Cd.).

Field experiments using two indica hybrid rice cultivars (IIyou28 and Ruiyou399), supported by microcosm studies, showed that ridge cultivation improved soil aeration, increased redox potential (Eh), and alleviated acidity. When combined with 1% (w/w) biochar or 0.05% P (w/w) CMP, grain As concentrations were reduced by 26.939.7% and Cd by 37.867.6% relative to ridge-only controls, without yield penalties. Microcosm results confirmed decreases in available soil As (26.3–31.2%) and marked reductions in soil solution As (75.6–82.5%) and Cd (to 0.13–0.15 $\mu g \cdot L^{-1}$).

The integrated treatment altered key soil properties, especially pH and Eh, enhancing interactions among Ca, Fe, Mn, and the target metals. Aerobic conditions promoted Fe/Al oxide formation for As immobilization, while Mn (hydr)oxides played a dominant role in Cd sequestration. Geochemical modeling and Aggregated Boosted Tree analysis identified these elemental interactions as primary drivers of reduced metal bioavailability. CMP exerted a liming effect and stimulated nitrification, lowering Cd-risk, whereas biochar delayed nitrogen oxidation and enhanced Mn-mediated stabilization.

Metagenomic analyses indicated that microbial redox cycling of Fe, Mn, and N was a critical control on metal mobility. CMP enriched ammonia-oxidizing genes (*amoA/B*), while biochar increased genes related to Mn (*mntC*) and Fe transport. Key taxa included Bradyrhizobiaceae (abundant in Mn and $Fe^{III}$ transport genes), Nitrososphaeraceae (linked to nitrification), and Caulobacteraceae (Fe transporters).

In conclusion, this study provides a mechanistic and field-validated basis for the integrated application of ridge cultivation with CMP and biochar as a sustainable remediation strategy for As-Cd co-contaminated paddy soils. By improving soil aeration, modifying redox dynamics, and enhancing both abiotic and microbial immobilization processes, this approach effectively reduces heavy metal bioavailability and accumulation in rice, ensuring both environmental and food safety. The findings offer significant implications for large-scale application in similar agroecosystems across Asia and beyond.

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# Impacts of Land Uses on Soil Quality in Western Patagonia

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## ABSTRACT

**Background:** Land use change (LUC) is one of the most important causes of climate change and soil degradation. In the last 5 years, the soil erosion rates at global scale have increased in 0.69 Pg $yr^{-1}$ and 0.20 Pg $yr^{-1}$ in croplands and grasslands, being the Global South the most affected area [1]. In Chile, 40% of the land is cover by bare soil and sparse vegetation, 24% by trees and 21% by grasslands. In the past (ca. 1550), the land in Southern Chile was covered by native forest (NF) and transformed to grasslands (G) and/or croplands (C). These LUC caused a detriment on soil functions; however, this process and the soil changes are still unknown in remote areas such as Western Patagonia. Human necessities are wide, and the soil is more than a food provider. Nowadays, society demands food, fiber and water produced in a clean and sustainable way that helps to mitigate climate change (e.g., carbon sequestration). The ecosystem services could be inferred through soil quality indexes, which depend on inherent (i.e., colloidal fractions) and dynamics soil properties [2] which are modified by soil management [3]. These changes caused by land reconversion could be evaluated from soil quality perspective, centered in the re-distribution of soil organic matter fractions [4].

**Objective:** To develop soil quality indices (SQI) in a climate gradient under contrasting land uses, considering inherent and dynamics properties and changes fractions of organic matter in soils of Western Patagonia.

**Methodology:** To cover the main environmental conditions in W. Patagonia xeric (X), mesic (M), and hydric (H) moisture conditions were be considered in the sampling design. In each condition, three land uses were selected; native forest (NF), grassland (G) and cropland (C). 3 pits were excavated by land uses to describe and took undisturbed and disturbed soil samples. 3 seasons and 2 depths were sampled (0-20 cm and 20-40 cm) to represent the surface and subsurface soil horizons. To determine the Al and Fe fractions, specific dissolution techniques were implemented, and physical, chemical, and biological properties were analyzed to build-up soil quality indexes. Soil organic matter fractioning is in progress to separate the particulate organic matter (POM) and mineral-associated organic matter (MAOM). Principal components analyses (PCA) and linear regressions were used to analyze the datasets. SQI were constructed by ecoregion and land cover for the functions of carbon storage *f*(C) and biomass accumulation *f*(BM).

**Results and Discussion:** The bulk density (BD) varied between 1.04 y 0.28 Mg $m^{-3}$ in xeric grasslands. The highest wide coarse pore volume (wCP = 29.7%) was found under NF soils which coincide with the maximum surface able to conduct air (Ka = 2.92 log $\mu m^2$). In xeric environments, BD explained the variability in wCP ($R^2 = 0.91$; $p < 0.001$) under croplands and wCP explained the Ka in NF conditions ($R^2 = 0.82$; $p < 0.001$). 66.6% of the variance was explained by two first PC. The PC1 (42%) was compound by ECEC, pH NaF, $Al_a$, Olsen-P and BD and PC2 (24.6%) by SOC, Total-N and pH $H_2O$. The soil reactivity increases from xeric to hydric conditions, which means changes in dominant colloidal fractions (*i.e.* from crystalline to amorphous), supported by the relationship between $Al_a$ and pH NaF ($R^2 = 0.90$; $p < 0.001$). SOC was inversely related to BD ($R^2 = 0.63$; $p < 0.000$) and directly related to Sulphur ($R^2 = 0.85$; $p < 0.001$). The functions of carbon storage were X = 0.6 < M = 1.2 < H = 2.4, while biomass ranged from: X = 2.8 > M = 2.4 < H = 2.9. SQI-*f*(C) were 33% higher in G = 1.7 than in C = 1.3, while for *f*(BM) the difference was 20% (G = 2.9 > C = 2.4).

**Conclusions:** Soil reactivity increases from east (xeric) to west (hydric) ecoregions, which have better soil conditions to store carbon, while for biomass accumulation function the differences are smaller among ecoregions. Grasslands have better potential than crops for performing the evaluated functions, however the transformation from native forest to grasslands and croplands affects the physical functions of soils in W. Patagonia.

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# Water quality and sediment analysis at selected locations of Imo River, Imo State, In Southeastern Nigeria.

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## ABSTRACT

There is a growing concern on the pitiable level of degeneration of water quality for irrigation and domestic purposes occasioned my incessant anthropogenic activities that have contributed to this menace. This Current investigation aims at insight about the level of contaminants of surface water and sediment analysis of selected locations of Imo river of imo State of Southeastern Nigeria over a twelve months period. The physico-chemical analysis was employed to assess the water and sediment quality of the samples. Air-shade temperature (28.6 - 29.6 0C), Surface Water Temperature (26.8 - 27.4 0C ), pH (6.2 - 6.6), Electrical conductivity (24.3 - 44.2 µscm-1), Total Dissolved Solid (11.8 - 21.1mgl-1), Total Hardness (82.3 – 99.6 mgl-1),Total Alkalinity (25.1 -39.2 mgl-1), Dissolved Oxygen (5.6 -7.8 mgl-1), Biochemical Oxygen Demand (2.5 - 3.7 mgl-1), Chloride (22.7 - 29 mgl-1) , Nitrate (0.4 -0.6 mgl-1), Sulphate (11.2-14.9 mgl-1), Silica (1.2 - 2.6 mgl-1), Total phosphorus (2.2-29 mgl-1), Potassium (1.5 - 2.5 mgl-1), Sodium (2.3 - 4.2 mgl-1), Calcium (0.6 - 1.02 mgl-1), Magnesium (0.9 - 1.3 mgl-1) , Zinc (0.01 - 0.02 mgl-1), Iron (0.14-0.50mgl-1) and Manganese(0.0 - 0.07mgl-1),while the following ranges were recorded for sediment: Temperature (27.6 - 28.6 0C), pH (5.5 - 5.8), Conductivity (93 - 211 µscm-1), Total Dissolved Solid (45.2 - 105 mgkg-1 DW), Manganese (2.4 – 19.5 mgkg-1 DW), Zinc (0.20 - 6.1 mgkg-1 DW), Iron (0.11 – 0.52 mgkg-1 DW), Potassium (5.76 - 11.8 mgkg-1 DW), Sodium (19.9 - 22.3 mgkg-1DW), Calcium (48.7 - 93.9 mgkg-1DW), Magnesium (3.6 -87.2 mgkg-1DW), Copper (0.0 - 0.01 mgkg-1 DW), Cadmium (0.0 -0.05 mgkg-1DW) and Arsenic (0.0 - 0.01 mgkg-1DW). All the values recorded for the physico-chemical parameters were within the range recorded for other water bodies of lower Niger Delta Region. They also fall within the permissible limit of S.O.N., W.H.O, E.U. and U.S.E.P.A. Standards except for dissolved oxygen and Ortho-phosphate phosphorus that slightly deviated. The Cationic order recorded for water column was: Na>k>Ca>Mg, While sediment cationic order was Ca >Na> Mg>K, with PFARSALL ‘S Index of 6.96mgl-1 (water) and 128.29 mgkg-1DW sediment. Air-Shade Temperature, Surface Water Temperature, Conductivity, T.D.S, Transparency, Total Hardness, D.O.,B.O.D., Chloride, Sulphate, Silica, Magnesium and Calcium showed monthly significant differences ($p < 0.05$), while Conductivity, T.D.S, Transparency, Silica and Calcium showed station/station significant differences ($P < 0.05$). Positive significant correlation were observed between Air-Shade Temperature and Total hardness, as well as dissolved oxygen with chloride ($p < 0.05$). The positive relationships observed depicts an interplay between the overlying water and the bottom sediment.

# Agriculture as a strategy to improve the food – water – energy nexus in Atlantic Forest, Brazil

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**ABSTRACT**

Global agricultural production is on a trajectory to double by 2050 due to both increases in the global population and the dietary changes associated with growing incomes. This increase also means more pressure on water resources, as agriculture accounts for 70% of global water withdrawal, and for energy production, as the whole food supply chain accounts for about 30% of total global energy consumption.

The water, energy, and food (WEF) nexus examines the interrelations among the three resource sectors, including the synergies, conflicts, and trade-offs that emerge from their management. These interconnections are extensive and significant. Managing one of them must not be treated in isolation but rather as part of an interconnected system.

Agriculture influences these three vital components of human livelihood that are being discussed here: food, water, and energy. The implementation of an ecosystem strategy to tackle agricultural food production can improve crop yield by utilizing ecosystem services that facilitate the decrease of external inputs, such as mineral fertilizers and pesticides. In this context, the principles of conservation agriculture (CA) serve as a central strategy because they enhance the use of agricultural resources by integrating the management of soil, water, and biodiversity, promoting multifunctionality in agriculture while also reducing reliance on external inputs. It can create synergies to maximize natural resource efficiency in alignment with societal objectives, boosting the WEF nexus strategy.

This study presents a novel methodology framework based on accessible secondary data to evaluate the impacts of three rural practices based on CA principles - agroforestry, spring protection, and pasture rotation - on the WEF nexus in the Atlantic Forest, southeast of Brazil, which is the Brazilian biome with the greatest population density within the country, hosting 72% of the population and contributing to 70% of the Brazilian GDP.

The results of the business as usual scenario indicated concern regarding water security, particularly in relation to sewage treatment and water commitment. The analysis revealed a similar pattern in energy security, with only two indicators showing positive performance. Conversely, a scenario of reduced vulnerability was observed in food security, as evidenced by the indicators of food production, nutritional value, and annual gross revenue. However, in the scenarios proposed by experts, the adoption of the rural practices that were assessed here can lead to consistent improvements in WEF security, evidencing the multifunctional capabilities of agriculture. Hence, the methodological framework presented here demonstrates its potential to be incorporated into decision-making processes to promote the multifunctionality of agriculture and sustainable use of rural areas.

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# Microbial innovation for nitrogen management in paddy soil: A success story of Endophytic Azotobacter chroococuum MCC 3432 (NRRI-EndoN)

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**ABSTRACT**

Among biofertilizers, diazotrophic bioinoculants are one of the microbial interventions for managing chemical nitrogen; but the potentiality of these microbes is really a question mark at field level mainly due to environmental constraints. Endophytes are less prone to environmental factors, therefore, *Azotobacter chroococcum* MCC 3432 (NRRI EndoN), a native endophyte diazotroph was harnessed as effective nitrogen-fixing bacteria for rice crop. NRRI EndoN was isolated from rice root and established its endophyte character by using FRET-based imaging technique. The potentiality of NRRI-EndoN was proved through lab and field study in rice crop. Finally, a liquid formulation of NRRI-EndoN, having shelf life of more than a year was developed and evaluated at 30 different locations covering about 1000 acres in the farmer's field. Based on validation data, NRRI-Endo N could enhance yield by 10.31% besides saving about 25% chemical N. The mean yield advantage of 0.53 t/ha could be achieved over farmer practice irrespective of rice cultivars which can lead to a monetary benefit of about 80 to 90 US dollar per hectare over farmers practice. The technology is certified by ICAR, India and Expression of Interest (EOI) has been published in AgriInovate, New Delhi, India for commercialization. For mass production, a large scale commercial biofertilizer production unit was established at CRRI which has capacity to produce 0.15 million liters annually. Revenue of around 35,000 US dollar was generated during 2024-2025 after selling of this product to different stakeholders. Besides, this product has been promoted through mass awareness, live demonstration, mass media and by existing farmer producing organization.

**Acknowledgments**

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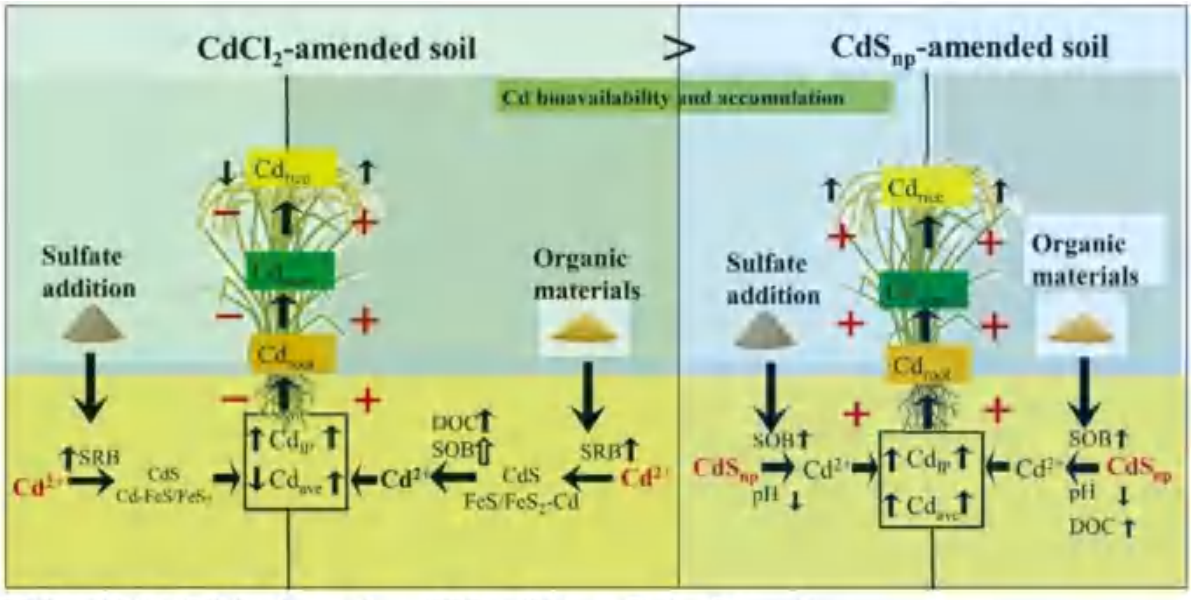
# Effect of organic materials and sulfate addition on cadmium bioavailability and accumulation of rice in cadmium sulfide nanoparticles- and cadmium chloride-treated soil

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**ABSTRACT**

Water-soluble and extractable cadmium (Cd) govern Cd bioavailability. However, cadmium sulfide nanoparticles ($CdS_{np}$) bioavailability remains unclear. Pot experiments investigated how organic materials (1 % wheat straw and pine needles) and sulfate (30 mg S/kg) affect Cd bioavailability and accumulation in rice in $CdCl_2$- and $CdS_{np}$-treated soils. Sulfate addition alone immobilized Cd through sulfate-reducing bacteria-mediated Cd-precipitation in $CdCl_2$-treated soil, thereby reducing Cd accumulation in brown rice. However, it promoted $CdS_{np}$ dissolution and Cd transfer, increasing Cd accumulation in $CdS_{np}$-treated soils. Organic materials alone promoted Cd re-release from immobilized Cd through sulfur-oxidizing bacteria (SOB)-induced oxidation and dissolved organic matter (DOM)-assisted complexation to increase Cd availability in $CdCl_2$-treated soil at the maturity stage. Consequently, organic materials alone increased brown rice Cd accumulation in $CdCl_2$-treated soil, while combination with sulfate had no effect. In $CdS_{np}$-treated soils, organic materials promoted $CdS_{np}$ dissolution through driving SOB, decreasing pH, and increasing DOM complexation, which increased Cd availability and transfer, promoting brown rice Cd accumulation. $CdS_{np}$ exhibited lower Cd bioavailability and accumulation than $CdCl_2$ due to lower solubility and slower Cd release, suggesting $CdS_{np}$ smaller contributions to rice Cd accumulation. Therefore, sulfate addition alone is recommended to reduce Cd accumulation, with organic materials only used in combination with sulfate.




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# Performance of sediment microbial fuel cells to inhibit arsenic availability in soil porewater: A laboratory study of three different Japanese paddy soils

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## ABSTRACT

Arsenic (As) contamination in paddy soils is a major environmental and agricultural issue. Sediment microbial fuel cells (SMFCs) have been operated as a sustainable method for reducing As mobility in contaminated soils while generating electricity. Soil factors such as Fe, Al, Mn, S, organic matter, pH, texture, and P levels affect As availability, but SMFC effectiveness across diverse soil types remain unclear. This study evaluated SMFC's impact on As availability in soil solutions from three Japanese paddy soils over an 80-day column experiment. Lab scale single chamber SMFC setups were established using cylindrical acrylic columns (height, 200 mm; diameter, 90 mm; thickness, 3 mm). Flame oxidized stainless steel mesh (180 × 40 mm) and carbon felt (60 × 50 mm) served as the anode and cathode materials, respectively. A total of 18 columns were constructed, and six sets of treatments were prepared in triplicate: Yamagata soil (Y-soil), Toyama soil (T-soil), and Kesennuma soil (K- soil) each operated under control (open-circuit (OC)) and SMFC-operated (closed-circuit (CC)) conditions. All the treatments were preincubated under OC conditions for one week at 25°C conditioned room, followed by 80 days of incubation. Cell voltages were recorded every 10 minutes throughout the experiment by a data acquisition system. Soil porewater was sampled for As and elemental analysis on days 0, 10, 20, 30, 40, 50, and 80 at 4 cm soil depth using samplers with 0.2 µm microporous membranes. Results showed that a maximum OC voltage of 1.1, 1.03, and 0.7 V, and CC voltage of 0.12, 0.2, and 0.15 V in T-soil, Y-soil, and K-soil treatments, respectively. The cumulative charge transferred by CCs was observed to be 329 C in T-soil, 501 C in K-soil, and 642 C in Y- soil, indicating varied electrochemical activity across the different soil types. Results further indicate that the operation of SMFC reduced available As in the soil solution by 12%, 20%, and 33% in T-soil, Y-soil, and K-soil, respectively compared to the controls. In T-soil and Y-soil, the concentration of As in the soil porewater was occasionally reduced by CCs during the first 50 days by keeping Fe and Mn steady perhaps through promoting oxidative process in the anode, which in turn inhibits arsenic release into the porewater. Eventually, the performance of SMFCs is likely limited by the depletion of organic matter required to suppress As release into the porewater of these soils. Whereas in K-soil the inhibition of As by CC continued until day 80, which correlates with higher levels ofFe, Mn, S, and DOC, supporting longer term reduction. Further statistical analyses showed that As correlated positively with pH, Ca, Mn, and Fe, but negatively with sulfur in pore water. Findings suggest that SMFC strongly affects As mobility in paddy soils, though soil chemistry may influence its remediation performance, extent and duration.

**Keywords:** heavy metals, paddy, power generation, remediation, soil solution

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# Synergistic modulation of Zinc Bioavailability in Alluvial paddy soil: Integrating Zn-solubilizing microbial consortia, cow dung, and mineral Zinc fertilizers for sustainable Rice production in India

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## ABSTRACT

Optimizing micronutrient use efficiency while minimizing chemical dependency is crucial for sustainable rice production. Zinc (Zn) deficiency remains a pervasive global challenge, affecting approximately one-third of cultivable soils. In submerged paddy ecosystems, Zn bioavailability is further compromised by elevated iron ($Fe^{2+}$) and manganese ($Mn^{2+}$) concentrations, which promote Zn adsorption onto hydroxide surfaces and the formation of insoluble compounds like franklinite ($ZnFe_2O_4$). While mineral fertilizers such as zinc sulphates provide highly soluble Zn, they are prone to rapid precipitation into unavailable carbonate or phosphate pools. This study investigates a synergistic "Inorganic-Organic-Microbial" approach using mineral Zn, cow dung, and zinc-solubilizing microbial consortia (ZSM)- *Acinetobacter calcoaceticus* and *Pantoea agglomerans* to enhance nutrient recovery efficiency and ensure long-term soil health. A two-year field experiment was conducted at the research farm of the Institute of Agricultural Sciences, Banaras Hindu University (BHU), Uttar Pradesh, India, located at 25°18' north latitude and 83°03' east longitude. The soil was alkaline in nature (pH 7.3) and had 0.78 mg $kg^{-1}$ DTPA-extracted Zn. The experiment was statistically designed in randomized block design (RBD), with twelve treatments and three replications. Among the treatments, plot received 9.8 kg ZnO $ha^{-1}$ with ZSM showed better biological yields, and outperformed the higher doses of mineral fertilizers applied in isolation. However, 25.0 kg Zn sulphate heptahydrate (ZnSHH) $ha^{-1}$ + ZSM was recorded statistically comparable to the former treatment. Notably, the addition of cow dung (CD) decreased the grain yield when combined with (9.8 kg ZnO $ha^{-1}$ + ZSM + 200 kg CD $ha^{-1}$) and (14.6 kg ZnO $ha^{-1}$ + ZSM + 200 kg CD $ha^{-1}$). Different use efficiency of applied Zn such as Partial factor productivity of applied Zn computed and it varied from 347.2 to 1762.2 and 369.6 to 1855.6 kg grain $kg^{-1}$ Zn, physiological Zn efficiency from 487.4 to 2075.3 and 775.5 and 2035.2 kg grain $kg^{-1}$ Zn, agronomic use efficiency of Zn from 20.1 to 189.6 and 28.7 to 180 kg grain $kg^{-1}$ Zn, the recovery efficiency of Zn fertilizer varied from 3.58 to 11.9% and 3.57 to 11.8% among the all treatments in both seasons, respectively. The recovery efficiency of Zn reached a maximum of 11.9%, representing a significant advancement in nutrient cycling compared to conventional practices. This research highlights a "microbial-organic-inorganic" triad that not only rehabilitates soil nutrient dynamics but also aligns with regenerative practices by reducing chemical dependency.

# Earthworm burrows enhanced rice root growth under a no-tillage rice-rapeseed rotation system

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**ABSTRACT**

Earthworm burrows are an important class of biopores that facilitate gas and water transport and affect plant root growth. However, in paddy soils that experience periodic flooding during the rice growth season, the effects of earthworm burrows on rice root growth have often been overlooked. In this study, we used X-ray Computed Tomography (CT) to investigate the impact of earthworm burrows on the growth of rice roots in paddy fields under two contrasting tillage practices. Undisturbed soil cores (0-36 cm depth) were collected from rotary tillage (RT) and no-tillage (NT) paddy fields, and then used for an incubation experiment that simulated a rice-rapeseed rotation system either with (RTE, NTE) or without (RTN, NTN) the addition of earthworms during the rapeseed season. Earthworm burrows, rice roots and their interaction were determined with CT imaging in the rice season. Rotary tillage resulted in 1.70 times greater soil macroporosity (>146 μm) than the NT soil. After earthworm introduction, the volume and surface area of earthworm burrows in the RTE treatment were 2.4 and 1.7 times greater, respectively, than those in the NTE treatment. However, the newly formed earthworm burrows in the RTE treatment did not significantly affect rice root traits or their utilization of these burrows. On the contrary, the increased earthworm burrows in the NTE treatment significantly enhanced rice root volume, surface area, length, mean diameter, and the utilization of these burrows by roots was 189% greater than in the NTN treatment. Additionally, the increase in earthworm burrows of the NTE treatment notably increased root density in the subsoil. Our results show that the increase of earthworm burrows has an important role in promoting rice root growth under NT, suggesting earthworms are crucial to the success of no tillage system for the rice paddies.

**Keywords:** Root-biopore interaction; Earthworm; No-tillage; Paddy soil; X-ray Computed Tomography

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# Carbon Storage Capacity of Peat Soils from High Bogs and Low Bogs

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**ABSTRACT**

Peat soils became now of more interest due to their potential to store atmosperic $CO_2$. There are attempts to increase areas covered by peat soils. This concerns primary high bogs by rewetting former peat land areas. Low bogs are not much in the focus of reestablishing peat land. However, they have a high potential to store atmosperic $CO_2$ in their dead and by water conserved plant mass.

The presentation will compare peats from high bogs and low bogs. $CO_2$ storage related to 1000 $cm^3$ peat and of peat profiles of 1 m depth will be given. The $CO_2$ storage is much depended on the bulk density of organic matter of peats. Thus about the bulk densities of the investigated peats will be reported too. Given examples are from the North German Low Land.

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# Human activities overrode natural climate controls on mercury deposition in Southern China during the late Holocene

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**ABSTRACT**

Peat is an important archive for reconstructing past ecosystems and human activities in mountainous regions. This study presents a high-resolution multi-proxy analysis of the Zhaogongting (ZGT) peatland in southern China, spanning the past ~9,000 years. We analyzed mercury (Hg) concentrations, pollen assemblages, total organic carbon (TOC), total nitrogen (TN), and stable isotopes ($\delta^{13}C$, $\delta^{15}N$) using quantitative modeling approaches, including stepwise multiple regression and eXtreme Gradient Boosting (XGBoost), to reconstruct environmental evolution and quantitatively evaluate the relative contributions of natural and anthropogenic factors to long-term mercury deposition. During 9.3–5 cal kyr BP, the ZGT area was probably a shallow, minerotrophic swamp, with relatively low Hg concentrations due to limited peat development and low atmospheric Hg inputs. Between 5 and 4 cal kyr BP, enhanced organic matter accumulation and cooler–drier climatic conditions promoted the transition to an ombrotrophic system, markedly increasing Hg retention. Around 4.2 cal kyr BP, synchronous changes across multiple proxies reflect a regional response to this cooling event. After 4 cal kyr BP, Hg concentrations continued to rise, with human activities such as widespread use and mining of cinnabar overtaking natural factors as the dominant control on Hg deposition. This study provides new quantitative evidence for the climate–peat–Hg coupling in subtropical East Asia and highlights the increasing anthropogenic influence on the remote area since the late Holocene.



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# Fungal biodiversity associated to alpine peatlands in northern Italy

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**ABSTRACT**

Peatlands are waterlogged areas where the rate of organic matter (OM) accumulation is greater than the rate of OM decomposition, thus resulting in the formation of peat, a complex material that consists of partly fossilized plant residues. Peatlands can be found in the arctic, boreal, temperate and tropical zones, and support a unique biodiversity in terms of plants, animals and microorganisms (bacteria, filamentous fungi and yeasts). Fungi are the main responsible for the degradation of recalcitrant peat components; on the opposite, yeasts are involved in the utilization of simple carbon compounds and are generally considered secondary saprotrophs. However, their ecological roles in this ecosystem still need to be clarified (Thormann 2006, 2007; Rydim *et al*. 2013; Juan-Ovejero *et al.* 2020). The aim of this work was to isolate and identify the culturable fungal community (filamentous fungi and yeasts) from peat. Samples were collected from two alpine peatlands (Northen Italy) at different depths, diluted 1:10 and plated on YM agar, supplemented with sodium propionate to inhibit filamentous fungi growth, and PDA agar. The identification was carried out with single or multi-locus sequences (LSU, ITS, benA, RPB2, tef1, ACT, GPDH3, HSP60). A total of 26 filamentous fungi and 12 yeasts were isolated.

The fungal taxa isolated from peatlands represent species that play fundamental roles in the OM decomposition. Some species rely on carbohydrates that leach out from plant tissues (e.g., *Cladosporium, Aureobasidium*), together with pioneer saprobes of OM derived from plant residues (e.g., *Linnemannia*, *Mortierella*, *Mucor*). Other taxa were identified as polymer degraders (e.g., *Fusarium*, *Trichoderma*). On the other hand, taxa associated with high activity in the degradation of recalcitrant polymers (e.g., lignin) were not detected; in fact, the isolates were mainly filamentous ascomycete fungi, whereas lignin degradation is primarily carried out by basidiomycetes. In addition, several plant pathogens were detected (*Fusarium commune*, *Didymella pomorum*, *Cadopohora luteo-olivacea, Zymoseptoria* sp.). Yeasts were also recovered, and most of them corresponded to taxa previously reported from peatland environments (e.g., *Cyberlidneria, Rhodotorula*).

Notably, the occurrence of the species filamentous fungi and yeasts species (such as *D. pomorum*, *Solicoccozyma aquatica*, and *Phaeotremella ovata*) represents a new record for this ecosystem. Furthermore, phylogenetic analyses showed that seven filamentous fungal taxa (*Chlamydocillium* sp., *Coniella* sp., *Myriosclerotinia* sp., *Cladosporium* sp., *Talaromyces* sp., *Coniochaeta* sp., *Zymoseptoria* sp.) and two yeasts (*Halobasidium* sp. and *Sterigmatospora* sp.) could not be assigned to any recognized species. Overall, this study revealed the fungal biodiversity associated with alpine peatlands in Italy, with particular emphasis on the isolation of taxa not previously recovered from similar environments, as well as putative new species.

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# The secret and fascinating world of the free-floating peat island of Posta Fibreno

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**ABSTRACT**

Free-floating islands, mysteriously moving around on lakes, were described by several Latin authors almost two millennia ago. Seneca (4 BC-AD 65) in his *Naturales quaestiones*, and by Pliny the Elder (AD 23-79) in his *Naturalis historia* ("Of Islands Ever Floating and Swimming"), for example, have left us suggestive descriptions of floating islands, reporting details about their size and shape, buoyancy and vegetation.

These fascinating ecosystems have been often investigated from ecological, hydrological and management points of view, but there have been almost no studies of their rates of accumulation of organic matter, as well as on their possible role as a natural archive of climate and vegetation changes, as well as of the historical human activity.

A 4-m long peat core was collected from the center of the free-floating island of Posta Fibreno, a relic mire in Central Italy. This is the thickest accumulation of peat ever found in a free-floating mire, yet it has formed during the past 700 yr (Zaccone et al., 2017). This free-floating mire shows anomalously high accretion rates (0.5–0.6 cm/yr), that are 10× greater than other terrestrial peatlands (0.02–0.08 cm/yr) (Zaccone et al., 2017), and preserves some peculiar microbial taxa (Zaccone et al., 2018) which show an unusual concurrent species convergence between this sub-Mediterranean site and far Nordic or circumpolar environments (Concheri et al., 2017). Thus, this free-floating island has the potential to be also used as archive of natural and human-induced environmental changes occurring during the last centuries.

In this work, the first high resolution records of organic matter accumulation, trace element and dust depositions, and environmental changes from a free-floating island will be presented, and the reliability of this peat archive for geochemical and environmental studies suggested and demonstrated.

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# Nutrient cycling in tropical peatland coconut agroecosystems integrating natural weeds as cover crops for sustainable management

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**ABSTRACT**

Tropical peatlands, vital carbon stores, are degraded by drainage, fires, and dependence on synthetic fertilizers, necessitating Nature-based Solutions (NbS) for sustainable management. While NbS frameworks promote nutrient cycling, empirical data on their crop-specific efficacy in perennial systems, such as coconut (Cocos nucifera) on peatlands, remain scarce. This study assesses regenerative practices in an organic-certified coconut estate (Indragiri Hilir, Indonesia), focusing on natural weeds as understory cover crops to implement the nutrient cycle. Seasonal sampling targeted natural weed biomass under coconut trees (n=12 randomized quadrats), soil (0–20 cm, n=12), and coconut leaves (n=9). Analyses included macro-and micronutrients, pH, and bulk density. The dominant fern (Nephrolepis sp., ~50% biomass) was manually weeded every 4 months and left to decompose in situ, emulating closed-loop nutrient cycling. The peat soil was acidic (pH 3.72 ± 0.19) with low base saturation but stable density (0.144 ± 0.01 g cm_3), indicating compaction recovery. Weed biomass averaged 7.8 ± 0.3 t DM ha_1 cycle_1, supplying ~19.8 kg P, 314 kg K, 97 kg Ca, 130 kg Mg, and 13 kg Na ha_1 yr_1 (with an average 75% of nutrient content released within 8-week periods). Leaf nutrient analyses revealed optimal status and no deficiencies, with yields comparable to those in fertilized systems. This approach delivered ecosystem services, including ~Rp 33 million (USD 1,985) ha_1 yr_1 in input savings, while contributing to minimized emissions and subsidence. The findings validate weed-mediated NbS for peatland perennials, offering scalable, low-cost alternatives amid fertilizer volatility. Replication in smallholder contexts could enhance socio-economic resilience and biodiversity, advancing sustainable peatland agriculture.

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# Depth controls on $CO_2$ emissions from drained agricultural peat soils and implications for national greenhouse gas inventories

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**ABSTRACT**

Peatlands play a central role in the global carbon cycle by storing a disproportionate share of the world's soil organic carbon. However, drainage for agriculture has transformed many peatlands from long-term carbon sinks into major sources of greenhouse gas (GHG) emissions. In particular, organic-rich soils transitioning from peat to organo-mineral soils represent a poorly documented component of national carbon budgets (Liang et al., 2024). At the same time, important knowledge gaps remain regarding how peat subsoils contribute to carbon dioxide ($CO_2$) emissions from drained agricultural peatlands and how this should be represented in GHG inventories and mitigation strategies (Kandel et al., 2025).

Here we report on depth-specific GHG fluxes from drained agricultural peatlands using intact peat cores collected from topsoil and subsoil layers at temperate arable and permanent grassland sites. GHG fluxes were measured across a gradient of temperatures and soil water tensions to disentangle the interacting effects of temperature, moisture and depth on GHG emissions. Carbon dioxide fluxes were consistently high-er in the topsoil than in the subsoil, with emissions on average three times greater, demonstrating that near-surface peat dominates short-term $CO_2$ losses. Temperature exerted a strong control on $CO_2$ emissions, particularly in the topsoil, whereas subsoil layers showed lower fluxes and reduced temperature sensitivity. Rewetting substantially reduced $CO_2$ emissions from topsoil at elevated temperatures but had little effect on subsoil fluxes.

Our results support modelling approaches that assume a decline in microbial $CO_2$ production with soil depth, consistent with sigmoidal water table depth response functions used in recent national inventory frameworks. However, the study also highlights uncertainties in linking annual mean water table depth to net $CO_2$ emissions, underscoring the need for improved depth-resolved process representation to enhance the accuracy of national GHG inventories and assessments of peatland rewetting as a climate mitigation strategy.

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# Breaking metabolomics limits for a molecular to pathway multidimensional analysis of metabolism alpine peatlands soil dissolved organic carbon

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**ABSTRACT**

As a critical component of the alpine peatland labile carbon pool, soil dissolved organic carbon (DOC) undergoes complex metabolic processes that are essential parameters for improving the understanding of soil carbon storage and mineralization systems, which have not yet been systematically elucidated. Traditional metabolomics and spectroscopy technology, as statistics-based compound analysis methods, fall short of providing a refined elucidation of the complex metabolic dynamics of alpine peatlands soil DOC (WDOC) at the molecular level. This study investigated the mineralization rate, changes in compound composition and quantity, and transformation of WDOC by integrating non-target metabolomics and spectroscopy with molecular simulation and comparative analysis against transformation databases. 84 samples were distributed along the tributaries of the Yellow river in the Zoige plateau, China. During the 0-48 hour in situ incubation, WDOC exhibited the highest metabolic rate within the initial 6 hours with 635 new compounds identified. The removal rate of topsoil WDOC (0-5 cm) (50.62%) was higher than that deep soil (15-20 cm) (47.34%). Compounds removed from WDOC were primarily unsaturated hydrocarbons, lignins, proteins, and lipids, characterized by O/C of 0-0.7 and H/C of 0.5-2.5. The newly produced compounds were mainly lipids and unsaturated hydrocarbons. Transformation-resistant compounds within WDOC are mainly low O/C (0-0.3) lipids and unsaturated hydrocarbons. Some tannin were retained during the metabolism of WDOC derived from deep soil contrast to topsoil. Comparative analysis of molecular simulations and the transformation database revealed that deoxygenation (30), demethylation (32), and decarboxylation (33) serve as primary pathways for the molecular transformation of WDOC. Microbial and photochemical processes transformed WDOC into more stable organic carbon with high saturation (DBE=6.4422), low aromaticity ($AI_{mod}$=0.1797), and high oxidation state (NOSC=-0.6655). Transformation pathways predicted across 3 levels via the KEGG database provided molecular level validation of WDOC metabolic processes. Compounds involved in WDOC metabolism were mainly found in metabolic pathways (ko01100), biosynthesis of secondary metabolites (ko01110), biosynthesis of cofactors (ko01240) and metabolism of xenobiotics by cytochrome P450 (ko00980) characteristic pathways.

**Keywords:** alpine peatlands; soil DOC; transformation; metabolomic

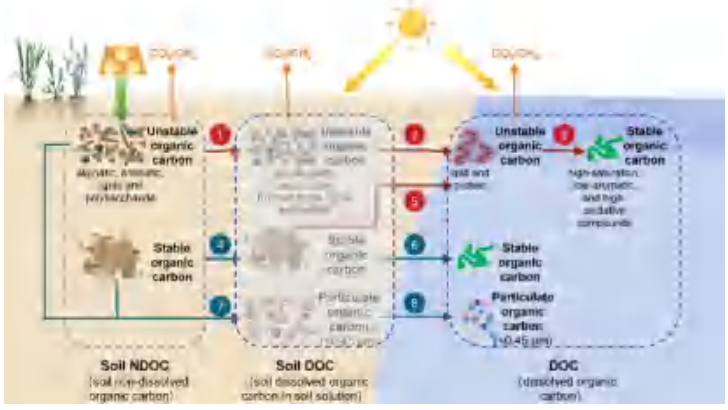



**Fig.1. Migration and transformation pathways of SOC in alpine peatland ecosystems**

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# Alpine peatlands degradation drives soil organic carbon mineralization but improves stability

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## ABSTRACT

Soil organic carbon (SOC) in alpine peatlands constitutes a major fraction of the global soil carbon pool and is assumed high sensitive to global environmental change especially soil moisture loss due to long-term low temperature environment. Despite soil moisture loss exacerbates the loss of alpine peatlands soil carbon pool, the response of SOC fractions to changes in soil moisture remain unexplored. Here we assess the mechanisms underlying the response of alpine SOC pools to soil moisture loss using a field survey of SOC in peat wetlands and dried peatlands (a peatland with degraded soil moisture) in the same ecological setting at the fraction scale. Despite a significant decrease in the SOC pool, the proportions of mineral-associated organic carbon (MAOC) and heavy-fraction organic carbon (HFOC) (more stable SOC forms) increased by approximately 25% and 20% in dried peatlands. We find that soil moisture loss caused about 40% of SOC mineralization and concentrated in the 0 - 15 cm soil layer. The larger size of particulate organic carbon mineralized up to 75 mg/g (about 60% of the total organic carbon), while about 39% for MAOC (smaller size). Soil dissolved organic carbon (DOC) decreased significantly in dried peatlands despite the smaller particle size (< 0.45 μm) of the more active soil DOC. From the density scale, the mineralization of HFOC is about 30 mg/g, which is much lower than that of light-fraction organic carbon (LFOC) (66 mg/g). While size and density scales are useful for explaining the stability of soil organic carbon based on its resistance to decomposition, direct supporting evidence is still lacking. We find that the content of more reactive aliphatic compounds decreased and the proportion of more stable aromatic compounds increased during soil moisture loss. The recalcitrance index (RI) and aromaticty (Ar), representing higher resistance to decomposition and more chemically stable structure, are significantly higher in dried peatlands ($RI_{DPL}$, 1.4-1.7; $Ar_{DPL}$, 2.0-10.1) than in peat wetlands ($RI_{WPL}$, 1.4-1.7; $Ar_{WPL}$, 2.0-10.1). The decrease of Gram-negative bacteria content, which is significantly positively correlated with more labile SOC, by 3.0 μmol/g in dried peatlands also indicated that stable SOC dominate the SOC pool in dried peatlands. Overall, our results find that soil moisture loss in alpine peatlands accelerate labile SOC mineralization at the size, density, compound and microbial scales but highlight the increased stability.

**Keywords:** Alpine peatlands degradation; SOC fractions; stability organic carbon; labile organic carbon

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# Soil nitrogen loss and altered plant nitrogen uptake following alpine peatland degradation: insights from nitrogen isotopes

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## ABSTRACT

Nitrogen plays a central role in regulating soil biogeochemical processes in peatlands; however, degradation of approximately 12% of global peatlands has substantially altered soil nitrogen cycling. Stable nitrogen isotopes ($\delta^{15}N$) are widely used to trace soil nitrogen sources and transformations, yet their responses to peatland degradation and associated controlling factors remain poorly constrained, particularly in alpine peatland soils. In this study, we investigated variations in soil and plant $\delta^{15}N$ and their relationships with soil nitrogen pools and environmental drivers along a degradation gradient in alpine peatlands of the Zoige (Ruoergai) peatland, eastern Tibetan Plateau, China, including flooded wetlands, wet meadows, moderately degraded meadows, and severely degraded meadows. Soil and root samples were collected across degradation stages, and $\delta^{15}N$ patterns were analyzed together with soil physicochemical properties. The result showed that soil $\delta^{15}N$ increased from flooded wetlands to wet meadows and moderately degraded meadows, indicating enhanced nitrogen mineralization and loss associated with peat drying and increased aeration. In contrast, soil $\delta^{15}N$ declined under severe degradation, likely reflecting constrained microbial activity and reduced nitrogen transformation capacity under strongly moisture- and nutrient-limited conditions. Across all degradation stages, plant roots were depleted in $^{15}N$ relative to soils, with progressively more negative $\Delta\delta^{15}N_{root-soil}$ values toward degraded sites, suggesting shifts in plant nitrogen acquisition pathways and isotope fractionation during uptake. Random forest results identified soil water content as the dominant control on soil and plant $\delta^{15}N$, followed by soil phosphorus and nitrogen availability, highlighting the interactive effects of hydrological change and nutrient limitation on soil nitrogen cycling. Overall, peatland degradation alters soil $\delta^{15}N$ signatures and enhances isotopic decoupling between soil and plants, reflecting a transition toward more open soil nitrogen cycling and increased nitrogen losses. These findings demonstrate the sensitivity of soil $\delta^{15}N$ to hydrological degradation and its value as an integrative indicator for assessing changes in soil nitrogen dynamics across peatland degradation gradients.

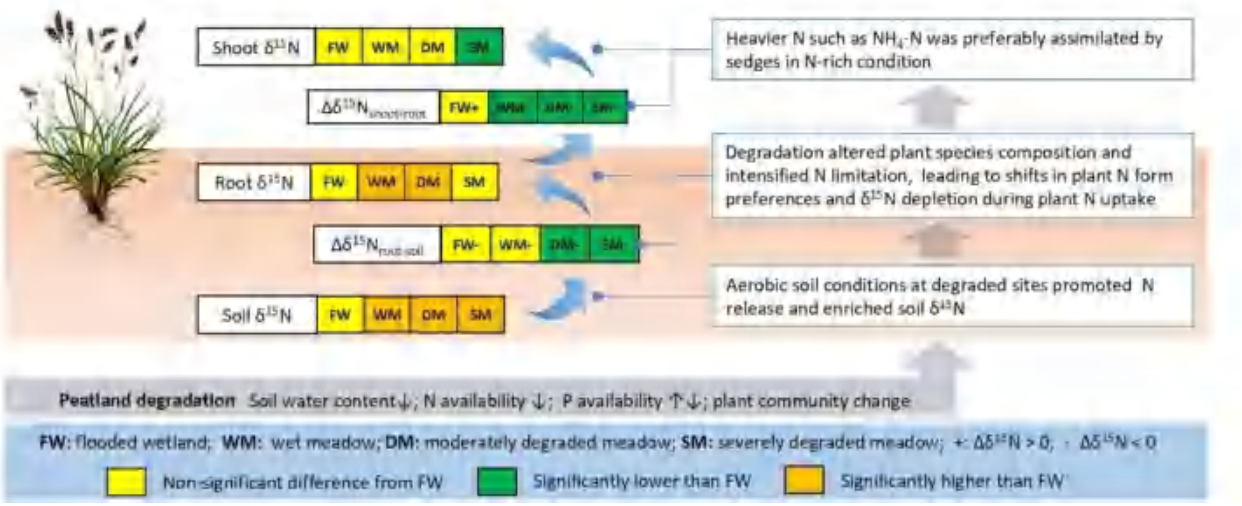



Figure. Schematic summary of changes in plant and soil characteristics with increasing peatland degradation severity.

# Soil drying accelerates CO2 emissions in global cold and wet ecosystems

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**ABSTRACT**

Cold and water-saturated ecosystems, including permafrost regions, northern peatlands, Arctic tundra, boreal wetlands, and alpine swamp meadows, store substantial reservoirs of soil organic carbon (SOC). These systems are widely recognized as being highly sensitive to climate warming, which accelerates SOC mineralization. However, at broad spatial scales, the extent to which soil water status modulates SOC decomposition and associated $CO_2$ emissions through its control on oxygen ($O_2$) availability remains insufficiently constrained. We combine *in-situ* measurements from 107 field sites with global observational datasets and process-based model simulations to examine how soil water dynamics regulate $CO_2$ emissions via limitations on $O_2$ diffusion across cold and wet ecosystems. Field observations consistently demonstrate that elevated soil water levels suppress SOC decomposition and $CO_2$ release, indicating that the removal of this hydrological constraint under drying conditions represents a key mechanism amplifying $CO_2$ emissions, in addition to the direct effects of warming. In contrast, global data-driven products and Earth system model simulations exhibit highly variable and often inconsistent relationships between soil $CO_2$ effluxes and soil water levels. Many current models rely on simplified soil moisture scalars or empirical parameterizations, which fail to adequately capture water-controlled $O_2$ diffusion and its impact on SOC decomposition in cold and wet environments. Our findings highlight the necessity of integrating more mechanistic representations of soil hydrological controls on SOC dynamics, alongside improved spatially explicit hydraulic properties, to strengthen projections of soil carbon-climate feedbacks.

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# Warming Amplifies Iron-Mediated Carbon Loss from Peatlands: A Positive Feedback Modulated By Soil Properties

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**ABSTRACT**

The vast organic carbon (OC) stocks in peatlands are highly vulnerable to global warming. While reactive iron (Fe) phases are known to regulate OC persistence, how warming affects the coupled Fe-OC dynamics in peatlands remains unclear. Through anoxic microcosm experiments with Zoige peatland soils (Qinghai-Tibet Plateau) across a temperature gradient (5–30°C), we demonstrate that Fe(III) reduction drove ~52% of anaerobic $CO_2$ production and mobilized substantial dissolved OC (DOC). FT-ICR-MS revealed that the mobilized DOC was selectively enriched in lower-molecular-weight, unsaturated compounds, whereas high-molecular-weight aromatic compounds remained more resistant to mobilization. Warming stimulated Fe-reducing bacteria (e.g., *Geothrix*), accelerating Fe(III) reduction and the concurrent release of $CO_2$ and low-molecular-weight DOC. The temperature sensitivities of $CO_2$ and DOC release were positively correlated with those of Fe(III) reduction. Soils with higher OC and reactive Fe(III) sustained greater rates of these processes but exhibited lower temperature sensitivity. Methanogenesis was disproportionately favored in OC-rich soils and at elevated temperatures. These findings suggest that warming will amplify Fe-mediated carbon loss and labile DOC export from peatlands, with the magnitude of this feedback modulated by inherent edaphic properties.

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# Harnessing the soil food web for sustainable ecosystems: Current evidence and future perspectives

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**ABSTRACT**

Terrestrial ecosystem function is governed by the intricate interactions among the constituent plants and soil biota. Plants fuel soil processes through carbon inputs and moderate biochemical cycles via ecosystem engineering, quantity and quality of litter deposition, and plant-soil biotic interactions. In turn, microbes drive nutrient mineralization fundamental to plant growth and directly influence plants as beneficial associates or as antagonists. In addition, the larger soil fauna modifies the soil physico-chemical landscape and regulate microbial activity, plant growth and ecosystem functions, and thereby plant community dynamics. A wealth of knowledge demonstrates the importance of the interactions among plants, microbes and soil fauna in driving ecosystem function, yet engineering of soil food web structure and biotic interactions to enhance ecosystem sustainability remains underutilized. In this presentation I will provide an overview of general principles of how better management (or engineering) of soil food webs can be applied across landscapes to both enhance the sustainability of production systems and restoring healthy and functionally resilient ecosystems to combat the ongoing biodiversity decline. I will leverage examples from ongoing research programs with collaborators and theory throughout the presentation. I will finish the talk by illustrating key knowledge gaps and perspectives on how we can better integrate knowledge of soil food web structure to future proof natural and managed ecosystems.

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# Coordinated plant-nematode ecological strategies shape soil carbon cycling

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**ABSTRACT**

An important aim of ecology is to understand the ecological strategies of organisms, how strategies relate to species traits, how traits and strategies of species affect ecosystem functions, and how these effects may be mediated by, or affect, other species. As for many aspects of the Earth, far less is known about the world belowground than aboveground. Although our knowledge has been advanced by ecological strategy schemes applied individually to plants, soil organisms and ecosystem function, evidence for their coordinated dynamics remains limited. Here, we take a holistic view to explore how the traits of ecosystem components – plants and soil nematodes – and of soil carbon cycling are coordinated across diverse ecosystems. We first identified a nematode trait space capturing two primary dimensions: the nematode economics spectrum (NES), balancing body construction costs against growth potential; and a reproduction dimension, varying from low to high fecundity. Regression analysis revealed their coordinated relationships with plant trait-strategy dimensions: the NES aligns with the plant economics spectrum (PES), and reproduction dimensions align with the root collaboration dimension. Notably, these coordinated plant-nematode trait dimensions correspond to distinct axes of soil carbon cycling: carbon fluxes are associated with the collaboration–reproduction dimension, whereas carbon pools are linked to the PES–NES dimension. This cross-kingdom coordination defines an integrated belowground trait space that provides a holistic perspective on ecosystem-level functional dynamics and opens new avenues for predicting ecosystem responses to changing environments.

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# Soil β-Diversity responses to global change: mediated by assembly processes and multi-trophic interactions

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**ABSTRACT**

Understanding how global change factors affect soil biodiversity through deterministic versus stochastic communities assembly processes remains a central challenge in ecology. We conducted a long-term multifactorial experiment to assess the impacts of drought, nitrogen deposition, and delayed snowmelt on soil communities. Using high-throughput sequencing for bacteria, fungi, and nematodes, and microscopic identification for mesofauna, we assessed the β-diversity and quantified the relative importance of assembly processes. Our results show that stochastic processes dominate in bacterial and mesofauna communities, whereas deterministic processes dominate in fungal and nematode communities. Drought increased the relative role of stochasticity in fungal and mesofauna communities but decreased it in bacterial communities. Nitrogen deposition enhanced stochasticity only in the fungal community. Furthermore, the degree of stochasticity in bacterial communities was positively correlated with their β-diversity, whereas the strength of deterministic processes was positively linked to β-diversity in fungal and nematode communities. Finally, we found that both within- and cross-trophic interactions jointly mediated the β-diversity of soil biotic community. Our findings demonstrate that delayed snowmelt can affect the impacts of drought and nitrogen deposition on soil biodiversity through multi-trophic interactions, providing new insights for grassland conservation and a critical theoretical basis for predicting biodiversity responses to global change.

# Effects of livestock grazing intensity on ground-dwelling arthropod communities in a desert steppe in Inner Mongolia

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**ABSTRACT**

Livestock grazing is known to significantly affect steppe ecosystems. However, the effects of grazing on ground-dwelling arthropods is still poorly studied, especially on the Stipa breviflora desert Steppe. We investigated the effects of varying intensities (light grazing (LG),moderate grazing (MG),heavy grazing (HG)as well as no grazing (CK) on the abundance and richness of ground-dwelling arthropods using pitfall trapping on August 2015. Plant communities and soil physicochemical characteristics were also measured to explore the relationships between the structure of ground-dwelling arthropod communities and key environmental variables.The abundance and group richness of ground-dwelling arthropods as well as the diversity index were significantly lower in the moderate and heavy grazing treatments ($P< 0.05$). Light grazing had no significant negative effect on ground arthropods, plant or soil characteristics($P>0.05$).Principal component analysis (PCA) showed that arthropod communities could be separated into two groups: control-light and moderate-heavy. Based on these results, light grazing may be an appropriate grazing intensity in this desert steppe.Partial redundancy analysis showed that community density and vegetation cover play the most important roles in regulating ground-dwelling arthropods responses to grazing.

# Mechanism of soil fauna on soil microbial necromass carbon accumulation in a subtropical forest under nitrogen addition

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**ABSTRACT**

Microbial necromass is an important source and component of the soil organic carbon pool and plays a crucial role in soil carbon cycle and climate change mitigation. Soil fauna, as the core of the belowground food webs, plays a critical role in controlling the formation and turnover of microbial necromass. However, due to the insufficient understanding of how nitrogen deposition affects soil fauna and their cascading effects on microorganisms, it is difficult to assess the contribution and regulatory role of soil fauna in microbial necromass carbon accumulation in the context of global change. To fill this gap, we conduct a field in situ manipulation experiment in a subtropical evergreen broad-leaved forest, three simulated nitrogen deposition treatments (i.e., 0, 50, and 150 kg N $ha^{-1}$ $yr^{-1}$) and two soil fauna treatments (i.e., non-defaunated and defaunated treatment) were established to examine to the effects of soil fauna on soil microbial necromass carbon accumulation in a subtropical forest under nitrogen addition. DNA metabarcoding and biomarker technology was used in this study to explore the effect of nitrogen addition on soil faunal communities and microbial necromass carbon contents. Soil microbial structure and function, key enzyme activities, and soil physicochemical properties were also be investigated. The main results are still under analysis, and we are confident of presenting a perfect report before the conference begins. We believe the results can provide theoretical support for further understanding the biological regulatory mechanism of the soil carbon cycle under the context of global change.

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# Proteobacteria as keystone bridges in the micro-food web: a new strategy for biocontrol design

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**ABSTRACT**

Trait-mediated interactions across trophic levels drive trophic cascades in macroecological systems, yet their relevance in microbially dominated soil ecosystems remains underexplored. We combined a regional field survey with controlled experiments using a defined 122-strain synthetic bacterial community and bacterivorous nematodes to test whether faunal predation reorganizes root-associated microbiomes to suppress soilborne disease. Field observations showed that sites with stronger nematode-Proteobacteria associations had lower bacterial wilt incidence. In controlled experiments, nematode predation selectively enriched Proteobacteria in the rhizosphere and reduced Ralstonia solanacearum populations and disease incidence. Preferential grazing drove this enrichment: Proteobacteria constituted over 95% of sequences in nematode guts, and focal taxa showed moderate antagonism, small cell size, and high metabolic activity. Together, these results identify Proteobacteria as key bridging taxa in cross-trophic interactions. Trait-linked responses to predation contribute to pathogen suppression and suggest a biocontrol framework that integrates microbial traits with trophic connectivity.

# Impacts of chemical free turfgrass renovation on soil arthropod and nematode communities

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**ABSTRACT**

Non-selective herbicides such as glyphosate have been used traditionally as the first and key step of turfgrass renovation. However, there has been an elevated public concern of exposure to chemicals in the USA and worldwide. One non-chemical alternative is light exclusion, which is more widely used in agriculture settings but not much on turfgrass management. This research proposed a turfgrass renovation approach using light exclusion that can reduce weed pressure when replanting turfgrass, switching turfgrass types, or completing a total renovation of a designated turfgrass area. In this study, we addressed the feasibility of using black, geo-textile weed mats made of woven polypropylene plastic in the alternative turfgrass renovation approach. The specific objectives were to test if this alternative approach can effectively renovate the turfgrass area, and to evaluate changes in the biotic communities in the soil indicated by arthropods and nematodes. This research was conducted at Magoon Research Station of University of Hawaii at Manoa on the island of Oahu, Hawaii. There are six steps to complete a chemical free light exclusion turfgrass renovation: 1) Cover existing weedy turfgrass area for about 6 weeks to eliminate all above ground vegetations; 2) Remove cover, and then remove dead weeds and turfgrass (and re-establish the desired site grade if necessary); 3) Fertilize to stimulate weed seed germination; 4) Allow for maximum weed seed germination and growth with overhead irrigation; 5) Cover the site a second time for about 3 weeks to eliminate newly emerged young weeds; and 6) Remove the cover for second time and re-plant new turfgrass. Our results indicated that the chemical free approach was effective in turfgrass renovation. Soil arthropod diversity and abundance changed significantly over time after each major renovation step. The largest diversity index values were seen after the first covering, and the lowest diversity values were seen after the fertilization and second covering. This trend was also observed for soil arthropod abundance, where the largest abundance occurred after the first covering, and the smallest after the fertilization and second covering. Soil nematode abundance (free-living nematodes and plant parasitic nematodes), maturity index, and combined maturity index were generally reduced after the turfgrass renovation steps. However, this
may not be an inherently negative outcome, especially when plant parasitic nematodes need to be managed in some turfgrass systems.

**Acknowledgments**

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# Greater trophic diversity of soil animal communities under agricultural land use and tropical climate

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## ABSTRACT

Soil fauna contributes to a wide range of ecosystem functions. Here, we investigate how trophic diversity of soil animals varies across functional groups and major biomes. We use stable isotope analysis ($^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios) of 17,306 samples of 28 high-rank taxa from 456 sites across 19 countries to inspect the variability in trophic diversity across climate regions and land-use types. Trophic diversity of soil animal communities is higher for microbial feeders than for detritivores and predators, in agricultural ecosystems compared to woodlands (+32%), and in tropical compared to temperate climates (+40%). Higher trophic diversity is related to more diverse basal resources and longer trophic chains, which could reflect greater niche partitioning in resource-limited environments. Our findings suggest that soil animals could broaden their trophic niches under agricultural land use and possibly in response to warming, but whether such foraging flexibility may offset the loss of trophic specialists remains to be investigated.

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# Leaving deadwood in canopy gap mitigates the decline of soil multifunctioning

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**ABSTRACT**

Worldwide, forest structure is being profoundly altered by intensifying disturbances that cause large-scale tree mortality. In unmanaged forests, disturbances leave both canopy gap and deadwood, whereas timber harvest creates gap but removes most deadwood. How these legacies of disturbances and management scenarios affect ecosystem functioning, especially belowground, remains unclear. Here, we reconstructed 116 soil animal food webs across 29 temperate forests in a full-factorial experiment manipulating canopy gap and deadwood addition. We quantified energy fluxes of soil food webs as an integrative measure of belowground ecosystem multifunctionality and characterized their network architecture. Canopy gap reduced total food web energy fluxes by 11.6% and decreased network connectance, while shifting energy flow towards the bacteria-dominated "fast" channel, indicating impaired ecosystem multifunctionality, simplified soil food webs and reduced energy retention belowground. However, the presence of deadwood in canopy gap increased total energy flux by 56.1% relative to gap without deadwood, mainly driven by enhanced fungivory and wood-feeding associated with elevated fungi-to-bacteria ratios in litter. Further, deadwood addition into canopy gap restored the network connectance and cycling rate to the level of closed-canopy forests. Our results demonstrate that deadwood acts as a critical structural component that buffers belowground ecosystem multifunctionality against canopy gap, highlighting deadwood retention as a key lever for sustaining soil functioning in disturbed forests.

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# Legume Intercropping Reshapes Aggregate-Scale Soil Micro-Food Webs and Nutrient Regulation in Tropical Rubber Plantations

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## ABSTRACT

Legume intercropping is widely considered an effective strategy to improve soil fertility and ecosystem functioning in tropical plantations, yet its mechanisms through regulating soil aggregate–scale soil micro-food webs remain poorly understood. In this study, we investigated natural forest, monoculture rubber plantations of different stand ages, and rubber-based agroforestry systems intercropped with the leguminous shrub Flemingia macrophylla in Xishuangbanna, Southwest China. Soils were fractionated into large macroaggregates, small macroaggregates, and microaggregates to assess bacterial, fungal, and nematode communities, their co-occurrence networks, and micro-food-web–mediated nutrient dynamics on soil nutrient availability. Results showed that land-use change was the primary driver of microbial and nematode community composition and structure, while aggregate size played a secondary but enhanced role in microaggregates. Rubber monocultures, particularly young stands, reduced microbial and nematode diversity and promoted plant-parasitic nematodes, leading to simplified food-web structures. In contrast, agroforestry systems effectively suppressed plant-parasitic nematodes, maintained higher microbial diversity, and enhanced cross-trophic interactions comparable to those in natural forests. Structural equation modeling revealed that stand change and soil aggregates regulated dissolved organic carbon, dissolved organic nitrogen, inorganic nitrogen, and available phosphorus through coordinated effects of soil pH, microbial diversity, enzyme activities, and nematode involvement. Aggregate structure dominated ammonium nitrogen regulation, whereas microbial processes played key roles in organic nutrients and phosphorus cycling. Our findings demonstrate that legume intercropping enhances soil nutrient dynamics by restructuring aggregate-scale micro-food webs, providing a sustainable management pathway for improving the stability and functioning of tropical rubber plantations.

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# Multi-trophic interactions in the rhizosphere promote network complexity to synergize with root genetic programs for improve P acquisition in maize

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## ABSTRACT

Understanding the regulatory mechanisms by which the rhizosphere micro-food web mediates phosphorus (P) absorption and utilization in maize roots is critical for improving P use efficiency. In this study, various P forms and P supply levels were established, high-throughput and transcription sequencing were respectively conducted on the maize rhizosphere soil and root, in conjunction with the the biologically based phosphorus (BBP) fractionation method. We aimed to elucidate the role of a representative micro-food web, which comprised protists, arbuscular mycorrhizal (AM) fungi, and P solubilizing bacteria, in driving the transformation of soil P forms and the underlying mechanisms of P uptake and utilization in maize roots. Our findings revealed that the components of the micro-food web responded differentially to P forms and supply levels, AM fungal α diversity was strongly affected by both P forms and application rate, whereas the α diversity of protists remained unaffected by both factors. Network analysis revealed that P application enhanced negative correlations among taxa, and trophic interactions mediated by protists were significantly positively correlated with network complexity. Root transcriptomic analysis identified P-responsive differentially expressed genes (e.g., *SPX*, *Phts*, and *PAP*), which were primarily associated with shoot P uptake. Metabolomic and Partial Least Squares Path Modeling (PLS-PM) modeling analyses further revealed that inorganic P enhanced maize P uptake by increasing root exudation of organic acids, which stimulates protistan predation on *pqqC*-harboring bacteria, thereby mobilizing the active rhizosphere P pool ($CaCl_2$-P and Citrate-P). Conversely, the organic P source (phytate) influences flavonoid-mediated interactions between *phoD*-harboring bacteria and predatory protists, regulating the stable P pool (Enzyme-P and HCl-P) and upregulating *PAP* genes and the phosphatase activity for organic P mineralization. In contrast, organic fertilizer, as a complex P source, integrates both pathways to promote P uptake. In summary, different P sources regulated rhizospheric enzyme activities and physicochemical properties, which shaped the community composition and stability of the micro-food web. These changes modulated multi-trophic interactions and synergized with P-responsive genes and rhizosphere metabolites to enhance P acquisition in maize. This study provids a scientific basis for levergaing the soil micro-food web to improve P-use efficiency and maize productivity.

**Acknowledgments**

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# Size-structured Energy Channeling in Soil Food Webs across Ecto- and Arbuscular Mycorrhiza-dominated Deciduous Forests

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## ABSTRACT

Soil animals form complex food webs that support nutrient cycling and organic matter turnover in forests. However, the role of soil faunal size classes in energy channelling remains unclear for ecosystems dominated by arbuscular (AMF) or ectomycorrhizal (EMF) fungi, which differ fundamentally in soil biogeochemistry. To address this gap, we combined compound-specific stable isotope analysis (CSIA-AA) of carbon and nitrogen and energy flux analysis to reconstruct soil food webs, examining energy channeling from basal resources (plants, fungi, bacteria) across nematodes, microarthropods, macroarthropods, and earthworms in AMF- and EMF-dominated deciduous forests. We found that despite moderate taxon-specific differences, total energy flux, its distribution among major channels (herbivory-detritivory, bacterivory, fungivory) and predation were similar between forest types. Across forests, energy channelling exhibited a consistent size-structured pattern: (1) the relative contributions of herbivory-detritivory and predation to total energy flux peaked in small nematodes and macroarthropods but were low in microarthropods and earthworms; (2) bacterivory was highest in the smallest (nematodes) and largest fauna (large macroarthropods and earthworms); while (3) fungivory peaked in small nematodes, microarthropods, and large earthworms but remained low in macroarthropods. These findings show high consistency of soil food web functioning across temperate deciduous forests and link the size spectrum of soil fauna to energy channeling and, therefore, to the ecosystem functioning of forest soils.

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# Drivers and Mechanisms of Biological Homogenization of Soil Protists in Human Land-Use Systems

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## ABSTRACT

Humans have substantially transformed the global land surface, leading to a decline in the variation of biotic communities across scales—a phenomenon termed biological homogenization. While this process has been widely recognized, the underlying mechanisms driving biological homogenization remain poorly understood, with critical knowledge gaps including: (1) the differential responses of distinct soil biotic taxa and functional groups to human land-use changes; (2) the relative contributions of the introduction of widespread generalist taxa versus the loss of narrow-ranged specialist taxa to homogenization; (3) the role of prey/host biota and environmental factors in mediating homogenization patterns; (4) the link between cross-regional dispersal of soil organisms and biological homogenization.

To address these knowledge gaps, we conducted a large-scale metabarcoding investigation of the biogeography of soil protists and their associated prey/hosts (prokaryotes, fungi, meso- and macrofauna). The study covered three human-dominated ecosystem types (farmlands, residential areas, and parks) as well as natural forest ecosystems across subtropical and temperate regions in China. We found that the degree of community homogenization varied markedly among soil protist taxa and functional groups, and was strongly positively correlated with their colonization ability in human land-use systems. In addition, the introduction of widespread generalist operational taxonomic units (OTUs), rather than the loss of narrow-ranged specialist OTUs, was identified as the primary driver of biological homogenization. Importantly, human land-use systems expanded the distribution range of generalists, predominantly facilitating the range expansion of temperate soil taxa into subtropical regions. This dispersal was largely enabled by increased soil pH in human-altered habitats that mitigates the natural acidity barrier of subtropical ecosystems. Finally, cross-regional spread of soil protists was more prominent in phagotrophs than in phototrophs and parasites, which reflects the co-dispersal of phagotrophic protists and their microbial prey (especially bacteria) due to tight predator–prey specialization and/or shared responses to environmental changes.

This study advances our mechanistic understanding of how human land-use changes shape soil biological homogenization, revealing varying responses of soil biota to land-use changes. Importantly, this variation is not random but predictable, and governed by their ability to colonize human land-use systems. Furthermore, our results provide important insights into how human land-use systems reshape the distribution pattern of soil biodiversity, highlighting that tropical and subtropical areas are likely to be disproportionately affected by biological homogenization driven by exotic species introductions.

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# Trophic interactions regulate the effects of long-term nitrogen enrichment on soil organic carbon

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## ABSTRACT

Eutrophication, including nitrogen (N) enrichment, can alter soil carbon cycling through changes in trophic interactions. However, it remains unclear how N enrichment affects the role of soil bacteria and fungi in regulating soil organic carbon (SOC) formation through changes in plant communities and soil nematodes. To bridge this knowledge gap, we employed an integrated research framework combining multiple experimental approaches. Firstly, our global meta-analysis revealed that N enrichment reduces microbial biomass in natural grasslands and forests primarily through soil acidification and declines in omnivorous-carnivorous nematodes. To further investigate these processes, we conducted a long-term gradient N addition experiment (initiated in 2000) in a typical steppe in Inner Mongolia. This study systematically monitored responses in plant communities, soil nematodes, microbial biomass and necromass carbon, and SOC physical fractions (particulate and mineral-associated organic carbon). Our findings demonstrated that N addition significantly reduces predatory nematode abundance, and further suppress the contribution of fungal necromass to mineral-associated organic carbon (MAOC). To directly quantify the contributions of bottom-up (plant-derived) and top-down (nematode-mediated) effects on SOC formation, we are currently conducting laboratory incubation experiments. These involve the addition of $^{13}C$-labeled root exudates and inoculation with key soil nematode functional groups. Using isotope tracing techniques, we will track the flow and stabilization of plant-derived carbon through the microbial–nematode food web. Collectively, this multi-scale experimental approach (spanning meta-analysis, long-term field observation, and controlled laboratory tracing) will elucidate how plant-nematode-microbe trophic interactions regulate SOC dynamics under N enrichment, offering mechanistic insights into the effects of N deposition on soil carbon sequestration.

# Testing the scaling effects and mechanisms of N-induced belowground biodiversity loss

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## ABSTRACT

Atmospheric nitrogen (N) deposition is widely recognized as a primary driver of belowground biodiversity loss. however, the extent of its impact and the underlying community assembly mechanisms remain poorly understood, largely due to a lack of explicit consideration for observation scale. Standardized sampling protocols often overlook scale-dependence, potentially obscuring the true sensitivity of soil fauna to environmental stressors. To address this, we systematically investigated soil nematode communities along a long-term N addition gradient (0, 1.75, 10.8, 28 g N $m^{-2}$ $yr^{-1}$) using a nested sampling design across three spatial scales (0.5, 10, and 100 g soil). This multi-scale approach allowed us to decouple the interactive effects of N enrichment and spatial heterogeneity on taxonomic diversity, functional structure, and community assembly processes. Our results revealed that N induced loss of nematode α diversity was not uniform but exhibited a strong scale-dependent amplification, with significantly steeper species loss at the macro-scale (i.e., 100 g) than at the finer scale (i.e., 0.5 g). Furthermore, N enrichment drove biotic homogenization (decline in β diversity), a pattern pronounced at larger scales where communities deviated farthest from their initial states. Mechanistically, community assembly shifted from deterministic filtering toward stochastic drift as scale increased. Specifically, N stress acted as a deterministic filter, selectively eliminating stress-sensitive K-strategists while favoring dispersal efficient r-strategists. This turnover was strongest at broader scales, thereby reinforcing stochastic dominance and leading to functional degradation. Importantly, these findings demonstrate that conventional small-scale sampling significantly underestimates the severity of N-induced biodiversity loss and functional decline. By elucidating the coupling between observation scale and N stress, this study provides a framework for accurately assessing belowground ecosystem vulnerability to global change.

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# The Effect of Soil Microorganisms on Organic Carbon Sequestration in Saline-Alkali Soils of the Hetao Irrigation District under Exogenous Organic Matter Addition

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## ABSTRACT

[Objective] This study aims to investigate the influence of soil microorganisms on organic carbon sequestration under the addition of exogenous organic materials in saline-affected agricultural ecosystems, thereby providing theoretical support and technical guidance for the remediation of saline-alkali soils in the Hetao Irrigation District. [Methods] Utilising the long-term fixed-site experimental base at the Wuyuan Maize Science and Technology Courtyard within the Hetao Irrigation District of Inner Mongolia, four organic materials (straw, cattle manure, sheep manure, biochar) were applied. The study examined the relationship between soil microorganisms and soil organic carbon at different aggregate scales.[Results] (1) Soil organic carbon ranged between 8.27 and 12.34 g·kg$^{-1}$. The sheep manure treatment yielded the highest organic carbon content in the whole soil at 10.82 g·kg$^{-1}$, followed by the straw treatment. Organic carbon in small aggregates under sheep manure treatment increased significantly by 14.8% compared to the control (CK). Medium aggregates exhibited higher organic carbon content than both large and small aggregates. Soil pH under straw treatment decreased by 0.02, 0.1, and 0.06 units in bulk soil, medium aggregates, and small aggregates respectively compared to the control. Goat manure addition reduced electrical conductivity in bulk soil and large aggregates by 10% and 34% respectively, with straw treatment showing the next greatest reduction.(2) In the whole soil, PLFAs from Gram-positive bacteria (GP), Gram-negative bacteria (GN), non-specific bacteria (Bact.), and actinomycetes (Actin.) were all significantly higher in the straw treatment compared to other treatments, increasing by 60%, 64%, 70%, and 59% respectively relative to the control (CK). In the three aggregate fractions, sheep manure treatment resulted in varying degrees of increase for all four bacterial PLFAs. Bacterial PLFAs in the whole soil were generally higher than those in the aggregate fractions.(3) The trends in fungal PLFAs (Fungi) and arbuscular mycorrhizal fungal PLFAs (AMF) across treatments were largely consistent with those observed for bacteria. In the whole soil sample, both Fungi and AMF showed significant increases under the straw treatment, rising by 56% and 78% respectively compared to the control (CK). Within soil aggregates, sheep manure treatment yielded higher Fungi and AMF levels than other treatments. Protist PLFAs exhibited markedly lower concentrations than bacterial and fungal PLFAs, with sheep manure treatment producing higher Protist levels in aggregates than other treatments.(4) Throughout the entire soil profile, GP, Actin., and Fungi exhibited a significant positive correlation with soil organic carbon. Within small aggregates, GP, Bact., Actin., Fungi, AMF, and Protists all showed a highly significant positive correlation with soil organic carbon. [Conclusion] The addition of sheep manure and straw enhanced the biomass of soil bacteria, fungi, and protists, thereby strengthening soil organic carbon sequestration and improving the physicochemical properties of saline-alkali soils. This holds significant implications for the remediation of saline-alkali lands in the Hetao Irrigation District.

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# Pesticide contamination in agricultural soils in Shanghai: residual characteristics and ecological risks to soil biota

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**ABSTRACT**

While pesticides enhance crop productivity, their persistence in soils threatens soil biota critical for ecosystem functions. Existing studies have inadequately characterized the contamination profiles and ecological risks of multiple pesticide residues in Shanghai's agroecosystems. Hence, this study investigated the occurrences of 70 pesticide residues in agricultural soils in Shanghai, assessed their ecological risks to soil biota, and identified the currently used pesticides warranting concerns. In total, 40 pesticides were detected, and the ranges of total concentrations were 11.76–296.33 $ng \cdot g^{-1}$, with the mean concentration of 83.71 $ng \cdot g^{-1}$. Contamination from pesticide mixtures has become widespread, with 52.94% of agricultural soils containing more than 5 species. Meanwhile, pesticide residues exhibited associations with cultivation methods, with greenhouse systems demonstrating 54.81% higher average concentrations compared to open-field systems, whereas crop type demonstrated a limited impact. Furthermore, individual pesticides mostly exhibited low exposure risks to soil biota including *Eisenia fetida*, *Enchytraeus crypticus*, *hypoaspis aculeifer*, *Folsomia candida*, and N-mineralizing microorganisms based on toxic exposure ratio (TER). In contrast, confronting the pervasive issue of pesticide mixture contamination, the Risk Quotient (RQ) assessment, taking into account the most sensitive soil biota, quantified integrated ecological risks posed by multiple pesticide. The results revealed that 33.82% of agricultural soils demonstrated high ecological risks ($RQ_{site} \geq 1$), indicating potential disruption to essential ecosystem function, and priority pesticides posing severe threats to soil biota were identified as *p, p'*-DDE, chlorpyrifos, bifenthrin, and metolachlor. Consequently, three currently used pesticides requiring priority attention were identified combing correlation analysis, hierarchical cluster analysis, and principal component analysis based on residual characteristics, ecological risks and pesticide properties: chlorpyrifos, metolachlor and terbuthylazine. This study provides scientific insights for developing environmental monitoring programs and management measures, ultimately contributing to ecosystem functions critical to sustainable agriculture.

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# Effects of earthworms and their combined application with functional attractant on soil organic carbon dynamics: Regulation of organic carbon fractions, aggregate formation, and their carbon sequestration

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**ABSTRACT**

Earthworms, as ecosystem engineers, regulate soil organic carbon (SOC) turnover through burrowing, feeding, and excretion behaviors. This study investigated the effects of *Metaphire guillelmi* and its co-application with a functional attractant (composed of saccharides, animal-derived, and plant-derived materials) on SOC dynamics via field experiments in orchards amended with decomposed cow manure. Results demonstrated that earthworms significantly increased SOC content by 15.90%, and facilitated the transformation of exogenous organic carbon into readily oxidizable carbon (ROC) and humic acids. This enhancement is primarily attributable to their capacity to elevate soil nutrient availability, primarily by enhancing nitrate nitrogen and available phosphorus. Earthworms also enhanced particulate organic carbon (POC) but had limited effects on mineral-associated organic carbon (MAOC). Regarding physical protection, earthworms elevated the proportions of large macroaggregates (>2 mm) and silt-clay fractions (<53 μm) along with their sequestered organic carbon, while improving aggregate stability, evidenced by higher MWD and GMD. Attractant alone slightly increased macroaggregate proportion, and its co-application with earthworms further promoted the formation of large macroaggregates and small macroaggregates (0.25-2 mm), simultaneously enhancing organic carbon in small macroaggregates. This study demonstrates that earthworms enhance SOC content and its stability, and their co-application with attractant promotes aggregate formation and its carbon sequestration, providing a theoretical basis for orchard soil carbon pool management and fertility enhancement.

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# Four decades of Soil Ecology: the good, the bad and the missing

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**ABSTRACT**

Soil Ecology studies interactions among soil organisms and their environment, emphasizing a holistic approach to soil biodiversity and ecosystem function. Because soils, and particularly organisms within them, are crucial for sustaining terrestrial productivity and mitigating climate change, increased financial support worldwide has enabled Soil Ecology research to advance at an unprecedented pace over the last four decades. The development of new techniques, such as isotopes and various spectrometry techniques, has greatly improved our capability to monitor and quantify biological transformations of nutrient elements and organic pollutants in soil. Notably, molecular techniques, including the increasingly popular metagenomics and meta-transcriptomics, have provided deeper insights into microbial populations, revealing previously unknown species or species consortia and clarifying their roles in nutrient cycling and disease resistance. Yet, development of Soil Ecology theories continues to lag, partly due to the complexity of soil ecosystems and a shortage of unifying theoretical frameworks. This presentation will revisit key milestones in Soil Ecology – including the introduction of the soil food-web model, the discovery of mycorrhizal networks, Comammox bacteria, the multifunctionality of trophic diversity, and advances in soil biodiversity research – to highlight their significance and discuss the major challenges facing soil ecology in the context of climate change and a growing human population.

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# Aggregate-Scale Microbial Communities: Spatial Heterogeneity, Potential food-webs & The Effect of Tillage

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**ABSTRACT**

What is a soil microbial community?
At what spatial scale does communities of soil microbes interact?
How does tillage change or disrupt these communities?

Despite growing awareness of the role of complex microbial food webs in soil functionality and ecosystem services, the specific compositions of soil food webs are yet to be discovered and their dynamics yet to be understood. Co-occurrence network analysis of environmental DNA amplicon-sequencing has been increasingly used over recent years to discern ecologically interacting microbial communities or soil food webs to understand better how they may be maintained or disrupted by environmental and land use change and agricultural management.

But there are two important methodological issues that make inferring microbial communities from these co-occurrence networks problematic (Goberna & Verdú, 2022). Firstly, the scale of sampling typically employed is an entire soil core (cm), homogenized and sub-sampled such that spatial heterogeneity is destroyed and averaged-over, making differences at the scale of microbial interaction and habitat, the (µm-mm) range, impossible to see. This study samples *individual macro-aggregates*, a sampling unit that acts as proxy for relatively stable and isolated pore space and that provides a sampling scale relevant to the life of microbes. Secondly, different microbial domains and broad trophic groups are typically targeted using separate amplicons and through separate laboratory pipelines making comparisons between bacteria, fungi and protist abundance impossible. This study employs internal standards based on a DNA construct spiked into the samples to quantify differences between bacteria, fungi and protist amplicons and to enable more meaningful assessment of which taxa are found together.

By combining these approaches, this study, for the first time, can discern the cross-kingdom microbial communities *at a scale in which they live and interact*. The aggregates sampled come from an experimental field trial employing both regenerative and conventional tillage practices and so the study can also see how mechanical soil disturbance can alter soil microbial communities.

The research answers the following questions:
- What is the spatial heterogeneity of bacteria, fungi and protist communities within the *cm* scale of a soil core and between *mm* scale macro-aggregates? And how does mechanical soil disturbance due to tillage affect this heterogeneity?
- What potential soil food-webs are harbored in the relatively stable and isolated pore space that macro-aggregates are a proxy for? And how does mechanical soil disturbance due to tillage affect the diversity, structure and composition of these potential soil food-webs?

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Supervisor team: Thorunn Helgason (University of Edinburgh) and Joe Taylor (UKCEH)

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# Investigating identification techniques and sample sizes effects on soil nematode community assessment

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## ABSTRACT

Nematodes are abundant and diverse in soil, and they can influence microbial community composition, plant performance, and nutrient cycling, serving as vital bioindicators for soil ecology and health. While metabarcoding techniques have become highly standardized in the identification of microbial (i.e., bacterial and fungal) communities, similar techniques are still under development for soil animals. As metabarcoding techniques become increasingly popular for characterizing soil animals, establishing protocols that are adapted to larger-bodied organisms is necessary. To optimize nematode metabarcoding workflows, we assessed how different identification techniques and soil sample sizes influence nematode ecological estimates and nematode community indices. We compared three identification techniques: traditional morphological identification, and two molecular methods using either nematode-extracted DNA or total soil DNA. Each technique was tested across varying soil size gradient (0.25 g – 32 g). DNA was amplified using nematode-specific 18S rRNA primers (Nemf/18Sr2b) and sequenced on an Illumina MiSeq platform. Sequencing data obtained from different protocols were processed using the DADA2 pipeline, followed by taxonomy assignment using the PR2 References database.

Our results demonstrated that nematode alpha diversity generally increased with greater soil mass, although significance was observed only for observed genera richness (q = 0). Morphological ID technique yielded the lowest genus counts, while soil DNA technique recovered more genera than nematode DNA in smaller samples. Community clustering revealed clear separation among the three identification techniques, especially between morphological and molecular methods, although community dispersion did not differ significantly among methods. Specific taxa were affected by technique and sample size; for instance, *Paratylenchus* and *Aphelenchoides* were significantly reduced in molecular data. Significant methodological differences were also evident among feeding guilds, particularly plant feeders, predators, and omnivores. Furthermore, soil mass significantly influenced key community indices, including the Structural, Plant-Parasitic, and Channel Indices. Together, these findings underscore that both methodological choice and sampling strategy critically shape the ecological interpretation of soil nematode communities, serving as a guide for the selection of appropriate protocols in soil nematode assessment.

# Fertilization Dictates Nematode-Microbe Trophic Interactions to Shape Plant Health and Soil Functions

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**ABSTRACT**

Fertilization practices profoundly reshape belowground trophic interactions, but how fertilizer regimes interact with soil nematodes to influence microbe-mediated pathogen suppression, nutrient cycling, and plant performance remains unclear. By integrating global meta-analyses with multi-omic profiling, machine-learning predictions, and field, greenhouse, and microcosm experiments, we demonstrate that fertilizer type is a major determinant of nematode-microbe-plant dynamics. Organic fertilizers promote bacterivore-dominated food webs that enhance plant productivity, strengthen the activity of pathogen-antagonistic bacteria such as *Bacillus*, and suppress the bacterial wilt pathogen *Ralstonia solanacearum*, whereas mineral fertilizers weaken these beneficial links and amplify negative herbivore-plant relationships. Microcosm experiments further show that bacterivorous nematodes such as *Protorhabditis* reduce $N_2O$ emissions by enriching Bacillus and denitrification genes (e.g., *nosZ*) through restructuring bacterial communities and stimulating microbial growth. Finally, multi-omic analyses reveal that root-knot nematode (*Meloidogyne*) invasion reprograms plant metabolism and disrupts rhizosphere homeostasis, shifting microbiomes from suppressive to permissive states by depleting antagonistic *Streptomyces* and enriching *Acidovorax* that synergizes with *R. solanacearum*. Together, these results show that fertilization fundamentally dictates the direction and strength of nematode-microbe trophic interactions, with major implications for disease suppression, greenhouse gas mitigation, and crop productivity.

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# Regulation of Soil Organic Carbon Fractions by Straw Return Duration via Microbial Community Shifts and Microbial Necromass Carbon

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## ABSTRACT

Soil microbial communities and microbial-derived carbon (MDC), including microbial biomass carbon (MBC) and microbial necromass carbon (MNC), are key drivers of soil organic carbon (SOC) dynamics under long-term straw return. However, how shifts in microbial community structure and life-history strategies under prolonged straw return affect MDC and subsequently alter SOC remains unclear. In this study, we employed 16S RNA sequencing technology to analyze the soil microbial community characteristics of maize fields in Northeast China under four different straw returning durations: 0 (0Y), 3 (3Y), 5 (5Y), and 7 (7Y) years. The results revealed that, compared to the no-straw-return treatment (0Y), straw return shifted microbial communities toward a stronger resource acquisition tendency. Fungal diversity decreased with increasing straw return duration, while bacterial richness increased. Bacteria employing the "resource acquisition strategy" (A-strategy), particularly Acidobacteriota, became dominant in the bacterial co-occurrence network. Further analysis of SOC and its fractions showed that MBC increased significantly with straw return duration, but the contribution of MNC to SOC declined. The rate of SOC increase slowed by the 7Y mark. These findings suggest that prolonged straw return promotes a shift in microbial life-history strategies toward resource acquisition, leading to reduced efficiency of microbial necromass carbon accumulation and consequently diminishing the effectiveness of SOC enhancement. Random forest analysis and path analysis indicated that MDC dynamics, shaped by changes in microbial community structure, drive the alterations in SOC fractions and overall SOC content as straw return duration increases. In summary, this study provides direct evidence of how microbial communities influence SOC through MDC and organic carbon fractions, offering a microbiological basis for black soil conservation and the development of agricultural carbon sequestration strategies.

**Acknowledgments**

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# Enchytraeid Bioturbation as a Key Driver of Microplastic Redistribution in Soils

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**ABSTRACT**

Microplastics have emerged as a global environmental concern, with soils acting as a major sink and posing risks to soil functioning and human health through entry into the food chain. Their bioavailability is closely linked to redistribution from point-source to non-point-source pollution during fragmentation and decomposition. Among the factors influencing this process, bioturbation by soil fauna plays a crucial role, yet research has been extremely limited and has largely focused on macrofauna such as earthworms and relatively coarse particle sizes. It is still unclear whether, and to what extent, smaller soil fauna can affect small sized microplastic redistribution at fine spatial scales. Here, we quantified microplastic transport by enchytraeid bioturbation both in vitro and in soil microcosms. Our results show that enchytraeids can transport microplastic beads of 2, 10, and 50 μm, with the highest transport capacity for 2 μm particles, relocating 1 ng over 9.8 cm after 3 days of incubation with 50 individuals in vitro. In soil microcosms, enchytraeids significantly increased the spread of 2 μm microplastics from the original location to surrounding areas, relocating $1\times10^3$ ng over 20.3 cm after 108 days of incubation. Overall, our findings demonstrate for the first time that enchytraeid bioturbation substantially enhances the transport of small-sized microplastics, highlighting bioturbation by soil fauna as a non-negligible mechanism of microplastic redistribution in soils.

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# Grassland management and time jointly shape the gut microbiome of soil collembolan Folsomia candida: A laboratory study

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## ABSTRACT

Grassland management practices profoundly alter soil properties and microbial communities, yet their effects on gut microbiota of soil animals remain unclear. Using the soil collembolan Folsomia candida as a model organism, this study employed indoor microcosm experiments to investigate changes in gut microbial community structure, function, and assembly mechanisms after 30 and 60 days of cultivation in soils from three typical grassland utilization types (enclosure, annual mowing, and heavy grazing) in the Hulunbuir Grassland. 16S rRNA gene sequencing analysis revealed that different treatments significantly altered the composition and diversity of collembola gut microbes. At the phylum level, Proteobacteria exhibited absolute dominance, though its relative abundance fluctuated across treatments and time. α-diversity (Chao1, Shannon index) differed significantly among treatments. β-diversity analysis (PcoA) confirmed that both grassland utilization type and incubation duration were significant drivers of community structure change. Functional prediction revealed alterations in key genes and pathways related to metabolism and signal transduction. Network analysis indicated differences in complexity and stability of microbial interaction networks across treatments. Further ecological process analysis (βNTI, niche breadth) revealed that deterministic processes (particularly homogenizing selection) dominated community assembly, while grazing enhanced the influence of stochastic processes. This study systematically reveals for the cascading effects of grassland management practices on collembola gut microbiota via the soil medium. It highlights the potential of soil animal gut microbiota as sensitive indicators of environmental change, providing new insights into soil animal-microbe interactions and their ecological functions within grassland ecosystems.

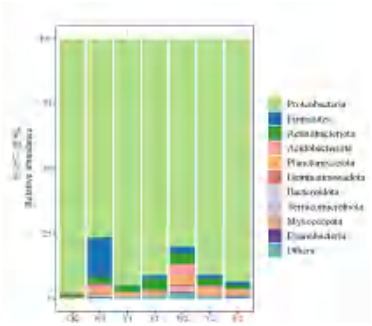


Figure 1 Dominant phyla of Folsomia candida gut bacterial communities

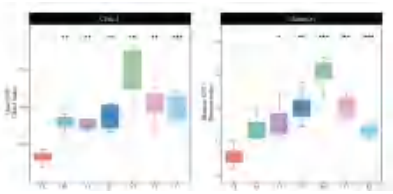


Figure 2 α-diversity indices of Folsomia candida gut bacterial community

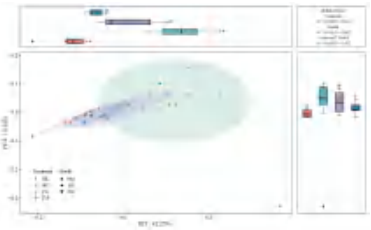


Figure 3 Folsomia candida gut bacterial community β-diversity analysis

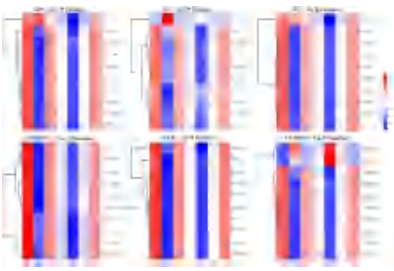


Figure 4 Functional profiles predicted for the Folsomia candida gut bacterial community

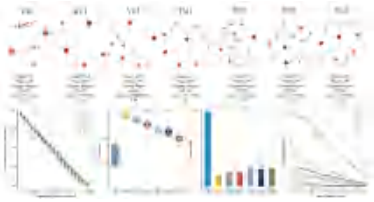


Figure 5 Co-occurrence network analysis of Folsomia candida gut bacterial communities and comparisons of network topological characteristics



Figure 6 Folsomia candida gut bacterial community assembly mechanism

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# Earthworm Responses to Veterinary Antibiotic Contamination in Soil and their Role in Mitigating Crop Toxicity

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**ABSTRACT**

Antibiotics, introduced in the 1940s, have been vital in controlling diseases and achieving economic gains. Yet, undigested veterinary antibiotics (VAs) excreted from livestock are increasingly contaminating terrestrial ecosystems. In agricultural soils, VAs in various concentration ranges have been detected, which is mainly considered a legacy of livestock manure application and wastewater irrigation. Notably, various types of VAs have been reported to have adverse effects on crop growth and development as well as productivity. As soil-dwelling fauna, earthworms can have high resistance to antibiotic toxicity while simultaneously facilitating the degradation of antibiotic residues and resistance genes in soil. This study was conducted to identify the sensitivity of earthworms to soils contaminated with major VAs such as chlortetracycline (CTC), sulfamethazine (SMZ), oxytetracycline (OTC), Penicillin (PC) etc. and to investigate the influences of earthworm addition on physiological responses and production of crop plants to VAs toxicity, via mesocosm experiments. The sensitivity test consisted of five concentration treatments of each antibiotic: 0, 50, 100, 250, and 500 mg/kg, and the incubation assay consisted of six concentration treatments of 0, 10, 100, 500, 1,000, and 5,000 mg/kg. In both experiments, adult earthworms (*Eisenia fetida*, >1 g) were selected, and field soil served as the test medium. For a pot experiment, CTC was applied to artificial soil at six concentrations (0, 1, 5, 10, 20, and 40 mg/kg), and one-week-old lettuce seedlings were cultivated for three weeks with or without the presence of *E. fetida*. Results from the sensitivity test revealed that earthworm avoidance patterns toward antibiotic toxicity changed with varying VAs treatments. SMZ and PC triggered the strongest avoidance in *E. fetida* at <100 mg/kg, while avoidance was universal at higher concentrations (to 500 mg/kg). In addition, the incubation assay showed that *E. fetida* exhibited no mortality in OTC, SMZ, and PC treatments, whereas exposure to CTC led to increased mortality at concentrations ranging from 500 to 5,000 mg/kg. Indeed, long-term bioassays showed increased biomass and soil water retention at 10–100 mg/kg CTC, reflecting earthworm tolerance to toxicity at these concentrations. According to the pot experiment, the fresh weight of lettuce shoots (the edible part) decreased by 34–47% at 5–40 mg/kg CTC compared with the control; however, the addition of earthworms prevented this reduction. Moreover, the presence of earthworms positively influenced plant physiology, as evidenced by enhanced photosynthetic efficiency (Fv/Fm), increased chlorophyll and anthocyanin contents, reduced oxidative stress indicators ($H_2O_2$ and malondialdehyde), and stimulated ascorbate peroxidase activity. These findings suggest that earthworms may alleviate CTC phytotoxicity by promoting plant growth, improving photosynthetic performance, and enhancing antioxidant enzyme activity.

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# Stage-specific microbial dynamics underpin ecosystem restoration on tropical coral islands

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## ABSTRACT

Despite the recognized benefits of diverse vegetation for terrestrial biodiversity and ecosystem services, its role in island ecosystem restoration remains poorly understood. We established five artificial vegetation types (grassland, windbreak and sand fixation, shelterbelt, public green space, roadside trees) on tropical coral islands and compared their soil properties and microbial communities with those of native forests. Artificial vegetation showed different levels of soil properties (except total potassium), microbial biomass (excluding fungi), enzyme activities, diversity indices (excluding fungi). Additionally, the community composition and network structure of soil microbes in artificial vegetation were distinct from those in native forests. Both ecosystems exhibited co-limitation by carbon and phosphorus. Fungi dominated in early restoration stages, while bacteria emerged as keystone drivers in later phases. Initial fungal inoculation accelerated vegetation establishment, and late-stage labile carbon inputs enhanced bacterial-mediated ecosystem stability. Phosphorus supplementation is recommended to alleviate nutrient co-limitation given that phosphorus is indispensable for microbial growth. Future research should focus on long-term dynamics to better assess restoration sustainability.

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This research was supported by the National Key R&D Program of China (Key Special Project for Marine Environmental Security and Sustainable Development of Coral Reefs, Grant No. 2021-400), the National Natural Science Foundation of China (Grant No. 32301565), the Science and Technology Planning Project of Guangdong Province (Grant Nos. 2024A1515011471 and2022A1515110990), and the Science and Technology Planning Project of Guangzhou City (Grant No. 2025A04J5432)

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# Ecotoxicity of Combined Thallium and Polylactic Acid Microplastics Pollution on the Functional Traits of Folsomia candida

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## ABSTRACT

Microplastics can bind to pollutants such as heavy metals through surface complexation and chelation, forming combined pollutants. However, research on the ecotoxicological effects of such combined pollution on soil fauna remains limited. This study, the model organism Folsomia candida was selected as the test subject, and a 28-day microcosm incubation experiment was conducted to explore the ecotoxicological effects of combined pollution by thallium (Tl) and polylactic acid microplastics (PLA-MPs) at different concentrations on Folsomia candida, focusing on functional traits including external morphology, biological characteristics, and gut microbiota. The results showed that high-concentration PLA-MPs (10%, w/w) had significant impacts on mortality rate and fecundity, significantly reduced gut bacterial community diversity, and reshaped the functional structure of the microflora by enriching Actinobacteriota, Bacteroidota, and Patescibacteria while inhibiting Pseudomonadota. Low-concentration (0.1%, w/w) and medium-concentration (1%, w/w) PLA-MPs drove the transition of gut bacterial community assembly from a deterministic to a stochastic process, reducing the contribution of heterogeneous selection while enhancing the importance of drift. In contrast, low-concentration Tl (1 ppm) significantly inhibited the body length and antenna length of Folsomia candida, while increasing the diversity index and niche breadth of the gut bacterial community. High-concentration Tl (10 ppm) promoted the relative abundance of Bacteroidota but inhibited that of Bacillota. The combined pollution of PLA-MPs and Tl exhibited certain synergistic or antagonistic effects on the functional traits of Folsomia candida. For instance, PLA-MPs exacerbated the inhibitory effect of Tl on the reproduction of Folsomia candida, while Tl could attenuate the disturbance effect of PLA-MPs on the gut microflora. The comprehensive effects of Tl and PLA-MPs on the functional traits of Folsomia candida were characterized by amplified combined effects and trait-specific responses. Compared with other indicators, external morphology was relatively insensitive to pollution stress. In conclusion, the combined pollution of Tl and PLA-MPs exerts significant negative effects on the functional traits of Folsomia candida by altering the abundance and assembly mechanism of the gut bacterial community, thereby regulating nutrient metabolism, immune defense, and energy allocation functions. The findings of this study will provide data support for understanding the ecotoxicological effects of combined Tl and PLA-MPs pollution on soil fauna, and contribute to assessing the ecological health risks of heavy metals and microplastics in soil.

# Rice straw return by water-logged press-bury in autumn Enhanced Black Soils Carbon Stability in Northeast China Paddy Fields

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**ABSTRACT**

Long-term intensified cultivation of paddy fields in Northeast China has triggered black soils degradation and threatened national food security. Although straw return has been widely accepted as an effective agricultural practice to restore soil structure and improve soil quality, traditional straw return approaches such as rotary tillage and deep plowing usually result in slow straw decomposition, straw floating under flooded irrigation and lower soil organic carbon sequestration. In the present study, a novel straw return approach termed as water-logged press-bury in autumn (WPB) was developed and a 3-year field experiment was conducted to examine variations in soils properties under three treatments: rotary tillage without straw return (RT), deep plowing with straw return (DP), and the WPB. Results showed that compared with the RT treatment, the WPB treatment significantly increased soil organic carbon (SOC) by 24.2%. In addition, the higher increments of particulate organic carbon (POC) (40.0%) and mineral associated organic carbon (MAOC) (53.2%) was found in the WPB treatment. The enhanced SOC stability in the WPB treatment was attributed to the physical protection of SOC by macroaggregates and the transformation efficiency of carbon sources by microorganism. Firstly, it was found that both the proportion of large macroaggregates（>2 mm）elevated by 15.3%, and the distribution of SOC fractions in macroaggregates by 12.68% and 42.26%. On the other hand, the proportions of alkyl C and O-alkyl C were increased by 5.4% and 5.0%, respectively, while the proportions of aromatic C and carboxyl C declined by 8.6% and 16.1%. This indicated the transformation of SOC towards a higher degree of humification. These findings provide a novel approach for returning rice straw to paddy fields in Northeast China, offering significant scientific and practical value for safeguarding black soils health and promoting sustainable agricultural development.

**Keywords:**black soils; paddy fields; water-logged press-bury in autumn; organic carbon; SOC stability

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# Gully Growth Rates in Northeast China

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## ABSTRACT

Gully erosion is a severe form of land degradation that threatens food production worldwide. A region substantially affected is Northeast China, where Mollisols dominate and which serves as the nation's greatest commodity grain base despite its relatively young arable history. Many field-based studies have quantified gully erosion and its drivers, yet individual studies always remain limited in spatial and temporal scope and thus cannot comprehensively assess the variation over time and space and its dominant natural and/or anthropogenic influences. Here, we compiled 475 records of gully growth from over 121,000 gullies in 40 studies to evaluate regional and temporal variation in gully growth across NE China. Geostatistical analysis indicated that all four growth rates, including length, area, volume, and density, exhibited pronounced spatial patterns. Approximately 80% of the gullies were concentrated in the northern parts of the Northeast Rolling Hilly and Sloping Region. The average gully length was 385 ± 423 m, with a maximum length of 3,733 m. Studies with an observation duration of less than 10 years showed significantly higher growth rates (10 ± 12 m $yr^{-1}$) than longer studies (6 ± 4 m $yr^{-1}$). Short-term (< 10 yrs) studies, especially in areas containing fewer than 50 gullies, are likely to be biased by extraordinarily large events which initiated the study. Gully growth rates increased with greater seasonal variability in temperature and precipitation, as well as with larger drainage areas. The pronounced difference in spatial patterns in different landscapes cannot be related to one simple climate or soil use variable. The pattern is the result of the interaction of several variables. Gully growth rates increased over time, particularly after the year 2000, creating an accelerating threat to China's breadbasket. Region-specific conservation measures are urgently needed to conserve soil and safeguard food security especially in Northeast China which is currently experiencing soil loss rates at 20 t $ha^{-1}$ $y^{-1}$.

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# Strip tillage combines the characteristics of conventional tillage and no-tillage in terms of soil macropore structure and hydrothermal conditions

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**ABSTRACT**

Sustainable utilization of Northeast China's black soils requires balancing exploitation and conservation. Conventional tillage (CT) enhances utilization but degrades soil, whereas no-tillage (NT) conserves soil and water but may reduce yield. Strip tillage (ST), combining tilled in-row zones (ST-IR) and non-tilled between-row zones (ST-BR) under straw mulch, integrates the advantages of CT and NT, offering a potential balance between productivity and conservation. However, its effects on soil macropore structure and hydrothermal properties remain unclear. This study employed time domain reflectometry (TDR) and X-ray computed tomography (X-CT) to evaluate soil hydrothermal conditions, key physical properties, and macropore characteristics under CT, NT, ST-IR, and ST-BR. Results showed that ST produced two distinct soil environments. The hydrothermal conditions, bulk density (BD), penetration resistance (PR), air capacity (AC), air permeability (AP), and available water capacity (AWC) in ST-IR were similar to those in CT. In contrast, ST-BR resembled NT but exhibited higher BD and PR, with markedly lower AC, AP, and AWC. Likewise, ST formed two distinct macropore structures. ST-IR aligned with CT, characterized by high macroporosity, large irregular non-biopores, and strong connectivity, with higher compactness (CP), specific surface area (SA), and fractal dimension (FD), but lower anisotropy (DA). Conversely, ST-BR and NT were dominated by elongated tubular biopores, showing lower macroporosity, CP, SA, and FD, but higher DA. Overall, ST integrates the structural and hydrothermal traits of CT and NT, forming a spatially heterogeneous system that supports both soil conservation and crop production. These findings enhance understanding of how ST promotes sustainable management of black soils.

# Spatial Patterns of Ephemeral Gullies and Their Impacts on Farmland and Crop production in the Black Soil Region of Northeast China

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## ABSTRACT

Gully erosion has become a major threat to farmland sustainability and food security in the black soil region of Northeast China, while most existing studies have focused on permanent gullies. Ephemeral gullies, which are characterized by their small scale, temporary nature, and tendency to be filled during tillage, have long been underestimated. Nevertheless, their widespread occurrence and frequent recurrence cause substantial but often overlooked losses to farmland and crop yield. More importantly, preventing ephemeral gullies from developing into permanent ones is crucial for effective erosion control. This study quantifies the spatial distribution of ephemeral gullies and their impacts on farmland and crop yield across multiple spatial scales. At the regional scale, a systematic survey was conducted across approximately 101,000 km² of the typical black soil belt. Ephemeral gullies within 620 small watersheds were visually interpreted from sub-meter-resolution remote sensing imagery and validated in 50 watersheds using UAV photogrammetry and GNSS RTK field measurements. A Random Forest based model integrating topographic, rainfall, soil, and crop factors was developed to map gully density. The interpretation accuracy reached about 80%, with an average gully number density of 4.02 per square kilometer and length density of 0.38 km·km$^{-2}$. Gully distribution was strongly controlled by topography; both slope gradient and slope length exhibited nonlinear threshold effects on gully density. At the watershed scale, UAV-based mapping and field measurements revealed a strong linear relationship between damaged farmland area (DFA, m²) and gully length (GL, m), expressed as DFA = 1.15GL, with an NSE of 0.89. At the hillslope scale, nine cross-sections were established across three representative ephemeral gullies, including 81 sampling points and two control sites. Ten soil physicochemical variables and eight crop trait indicators were analyzed. Results showed that corn and soybean yields decreased by 14.35% and 36.85%, respectively, within 3 m from the ephemeral gully bottom, and total crop failure occurred within 1 m downslope. The study elucidates a process chain linking ephemeral gully formation, microtopographic alteration, soil degradation, crop stress, and yield reduction. This work provides a multi-scale quantitative assessment of ephemeral gully spatial patterns and their agricultural impacts in the black soil region of Northeast China. The findings offer theoretical and practical support for developing preventive and integrated gully erosion control strategies in fragile agricultural landscapes.

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# Health regulation of black soil under the dual carbon strategy

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**ABSTRACT**

Black soil is a vital agricultural resource characterized by high fertility, formed through the accumulation of humic substances under unique climatic, vegetative, and topographic conditions. As China pursues its "Dual Carbon" strategy, the Northeast Black Soil Region plays a dual role as a cornerstone of national food security and a critical terrestrial carbon sink. However, long-term intensive farming has led to severe degradation, marked by declining organic matter, thinning of the fertile layer, and accumulation of pollutants such as pesticides, plasticizers, antibiotics, and heavy metals. These challenges threaten both soil health and agricultural sustainability.

To address these issues, research has focused on agricultural carbon neutrality and soil remediation. Innovations include developing cold-tolerant microbial agents for degrading pesticides and plastic films, creating biochar-based biofertilizers, and advancing integrated "remediation while producing" strategies. Techniques for expanding the soil plow layer, enhancing soil organic matter, and facilitating straw decomposition have been implemented to synergize agricultural productivity with ecological restoration. A comprehensive technical system has been established, encompassing in-situ remediation, saline-alkali soil improvement, and precision nutrient management. Supporting these efforts, monitoring protocols and digital platforms for fertilizer and pesticide reduction have been developed to guide sustainable soil management.

Aligned with carbon neutrality goals, an integrated "Block-Increase-Stabilize" framework has been introduced to enhance carbon sequestration. This approach combines conservation tillage to minimize carbon loss, deep loosening and organic amendments to boost carbon input, and biochar-humic acid composites to stabilize soil carbon pools. For pollution control, functional microbial agents and biochar-based materials have been engineered to degrade chemical residues and immobilize heavy metals, enabling productive and eco-friendly agriculture. These advancements provide a scientific and practical foundation for achieving green development in black soil regions, ensuring food security, and fulfilling carbon sequestration targets..

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# Microbial-Mediated Mechanisms Underlying Soil Fertility Stability in the Northeast Black Soil Region of China

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**ABSTRACT**

The Northeast Black Soil Region is vital for China's grain production. Maintaining its fertility is crucial for national food security. Long-term intensive use and unsuitable fertilization have caused soil degradation. Understanding how soil organic matter (SOM), microbes, and soil structure interact under stable, long-term fertilization is key for sustainable management. This study, based on 25-year trials in four soil types (Black, Brown, Dark Brown soil) with stable fertility, compares four treatments: mineral fertilizer (NPK), organic manure (M), combined fertilization (MNPK), and no fertilizer (CK). We analyze three aspects: SOM stability, microbial traits, and soil structure stability, to uncover microbes' role in linking SOM and structure.

For SOM stability, we measured not just total organic carbon but also its quality. Analyzing fractions like particulate and mineral-associated organic carbon shows how different fertilizations affect carbon pools. Studying humus components reveals chemical stability. This identifies which SOM fractions are key for long-term fertility and how MNPK best enhances both active and stable carbon pools.

In microbial traits, we see microbes as the link between organic inputs and soil carbon/structure. We measure microbial biomass, community structure (using PLFA and metagenomics for diversity/species), and function (carbon metabolism genes). Amino sugars, as microbial residue markers, show how much microbes contribute to stable SOM, highlighting the "microbial carbon pump."

For soil structure stability, we focus on aggregates, which protect SOM and host microbes. We measure aggregate size distribution and stability (e.g., mean weight diameter). Advanced pore structure analysis (via CT scanning) shows how MNPK improves soil structure. Aggregate stability is closely tied to organic matter and microbes, connecting these three components.

Our main goal is to integrate all data to build a model of the SOM-structure-microbe relationships under stable fertility. We will use statistical models to test our hypothesis: MNPK supports a diverse, functional microbial community that drives stability by 1) using carbon to build its own biomass and residues, enriching stable carbon; 2) forming stable aggregates that protect carbon; and 3) creating better soil habitats that further support microbes, forming a positive loop.

In summary, this multi-dimensional study explains the synergistic mechanism where microbes mediate SOM and structure stability under long-term MNPK in black soils. It provides a theory for sustainable soil management focused on building healthy soil ecosystems.

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# Black Soil Degradation in Northeast China and its Driving Factors

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## ABSTRACT

The black soil region in Northeast China plays a crucial role in national food security. However, decades of intensive cultivation have caused soil degradation. Although the degradation of black soils has been widely recognized, unclear boundaries and the limited spatial coverage of previous soil data have constrained the assessment of degradation extent and dynamics, while also limiting the quantification of key driving factors behind changes in soil thickness, fertility, and compaction.

To overcome these limitations, data from the 3rd National Soil Survey (2022–2025) were integrated with the 2nd National Soil Survey (1980s) to establish a standardized procedure for delineating the black soil boundary and assessing its degradation. The study covered the region in Heilongjiang, Jilin, and Liaoning provinces and the five eastern leagues or cities of Inner Mongolia (Xing'an, Xilingol, Hulunbuir, Tongliao, and Chifeng), using 10,071 soil profiles from the 3rd and 6,731 profiles from the 2nd National Soil Survey. The black soil horizon in each profile was identified, and its thickness was calculated by summing all recognized black horizons, excluding horizons buried deeper than 50 cm. Point observations from the 3rd and 2nd soil profiles were combined with environmental covariates in a machine-learning model to map black soil horizon thickness for current and historical periods. By overlaying each thickness map with cropland boundaries and the eight black-soil-related soil types (Phaeozem, Chernozem, Kastanozem, Meadow soil, Dark brown soil, Brown soil, Albic bleached soil, Paddy soil), the current and historical extents of black soils were delineated. The union of these two extents was defined as the final black soil region. Within the black soil boundaries, degradation over the past four decades was quantified by comparing soil organic matter, bulk density, and black soil horizon thickness between the 3rd and 2nd Soil Surveys. The degree of degradation was classified, and the thresholds for black soil thinning, fertility decline and compaction, were established and normalized to a [0–1] scale to construct a degradation assessment index. In addition, environmental covariates and land-use data were incorporated to quantify the relative contributions of different driving factors to black soil degradation.

Our results produced a high-resolution (30×30 m) map of black soil horizon thickness and delineated the boundaries of black soil region. Comparative analysis showed a widespread decline in black soil horizon thickness and a shrinkage of the black soil area, while other soil properties showed regional variability, indicating degradation in several core areas. The study establishes a standardized method for delineating the black soil region and identifies the driving factors of black soil degradation in Northeast China, providing scientific basis for its conservation and restoration.

**Keywords:** Black soil; Soil degradation; Machine learning; Food security

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# Spatial heterogeneity of soil C-N-P stoichiometry and its controlling factors in agricultural soils across the Songnen Plain, Northeast China

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**ABSTRACT**

The stoichiometric characteristics of soil carbon (C), nitrogen (N), and phosphorus (P) play a fundamental role in maintaining soil fertility, regulating ecosystem sustainability, and influencing crop growth. However, currently, there is still a lack of understanding of the spatial distribution patterns and driving mechanisms of C, N, and P stoichiometry. In this study, soil samples from 225 sampling points in the Songnen Plain were analyzed. Geostatistical methods and Empirical Bayesian Kriging interpolation were used to map the spatial distributions of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and their stoichiometric ratios. Additionally, feature importance analysis and correlation analysis were employed to explore the effects of various factors on the soil C:N:P stoichiometric ratios. The results showed that the contents of SOC, TN, and TP exhibited a spatial distribution pattern of higher values in the north and lower values in the south. The average values of the C:N, C:P, and N:P ratios were 11.58, 32.78, and 2.84, respectively, with different spatial distribution characteristics. Feature importance analysis identified SOC as the most critical factor influencing the C:N:P ratios (importance values approximately 0.5~0.6), showing significant positive correlations with these ratios. Among the climatic factors, the mean annual temperature was significantly negatively correlated with the C:N:P ratios (correlation coefficients about -0.2~ -0.34), while the annual precipitation mainly affected the C:N ratio. Different soil types also had significant effects on the C:N:P ratios, with black soil exhibiting the highest C:N and C:P ratios (11.8 and 36.7, respectively). This study provides important scientific evidence for understanding the nutrient balance in farmland soils of the Songnen Plain and its influencing factors, which is of great significance for developing sustainable soil management strategies.

**Keywords:** Songnen Plain; C:N:P stoichiometry; Spatial distribution; Influencing factors

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# Multi-temporal monitoring of crop residue cover for large-scale classification of tillage practices: linking deep learning of UAV images with satellite-based spectral modelling

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## ABSTRACT

Obtaining spatially and temporally explicit information on agricultural management practices is crucial for accurately modeling soil organic carbon dynamics and verifying the impact of carbon farming activities. Conventional field-based and remote sensing surveys struggle with insufficient spatial and temporal coverage to capture the dynamics of crop residue cover (CRC) across large scales. Focusing on the various residue management practices in Northeast China, we will present a temporally transferable CRC mapping approach, by integrating deep learning of unmanned aerial vehicle (UAV) images with Sentinel-2 multispectral modelling.

A modified U-Net image segmentation algorithm with a ResNet-50 backbone was trained to generate CRC observations at high accuracy and efficiency. Independent tests showed satisfactory segmentation performance (mPA=92.02%), outperforming the traditional OTSU method by more than 30%. Through deep learning of UAV images, we developed a multi-seasonal CRC dataset across the Songnen Plain of Northeast China.

UAV-derived CRC ground References was then linked with Sentinel-2 surface reflectance for spectra-based CRC predictive mapping. The spectral model, trained on spring 2024 observations, demonstrated robust transferability, accurately predicting CRC in autumn 2024 ($R^2$=0.85, RMSE=12.64%) and spring 2025 ($R^2$=0.70, RMSE=10.05%). This temporally transferable framework thus enabled spatiotemporal monitoring of crop residue cover for large-scale classification of tillage practices. The mapping products revealed distinct residue retention patterns between conventional (abrupt clearance) and conservation tillage (persistent coverage). This work establishes a physically meaningful, transferable framework for field-level tillage classification and large-scale monitoring of conservation agricultural practices and their impact on soil carbon dynamics.

**Key words:** crop residue management, tillage classification, remote sensing, soil degradation, carbon farming

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# Effects of Furrow Straw Mulch on Soil Erosion and Organic Carbon Redistribution in Soil Aggregates at Sloping Farmland

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**ABSTRACT**

The severe soil erosion at sloping farmland leads to soil structure destruction and organic carbon migration, threatening agriculture sustainable development. Furrow straw mulch effectively prevents soil erosion, but research on distribution characteristics of soil organic carbon on hillslope remains insufficient. This study designed ridge tillage without (CK) and with furrow straw mulch on 3°, 6°, and 9° hillslope of the Chinese black soil region to analyze soil erosion modulus (EM), soil erodibility (K), soil aggregate structure, stability, and organic carbon content at upper, middle, and lower hillslope positions after an 11-year situ monitoring study under natural rainfall and farmland conditions. The results showed that the soil erosion modulus ranged from 764.56 to 2214.84 $t \cdot km^{-2} \cdot a^{-1}$ at 3°, from 1415.78 to 3798.79 $t \cdot km^{-2} \cdot a^{-1}$ at 6°, and from -139.06 to 1839.07 $t \cdot km^{-2} \cdot a^{-1}$ at 9° for CK treatments. In contrast, the soil erosion modulus decreased by 40.89%-53.19% at 3°, 77.05%-116.56% at 6°, and 20.01%-481.25% at 9° for furrow straw mulch treatments. Furthermore, the K also decreased by 0.02%-0.95% and the percentage of aggregate destruction (PAD) decreased by 6.10%-38.39% for furrow straw mulch compared with those of CK for hillslope with different slope gradients. Meanwhile, the proportion of water-stable aggregates (>0.25 mm) increased by 0.30%-32.70%, the mean weight diameter (MWD) increased by 1.90%-58.50%, and soil organic carbon content in macroaggregates increased by 6.09%-102.69% at all hillslope positions. Therefore, furrow straw mulch not only decreased soil erosion at sloping farmland but also improved soil aggregate stability and increased soil aggregate organic carbon sequestration capacity.

**Keywords:** Furrow straw mulch, Soil aggregate, Soil organic carbon, Soil erosion, Black soil region.

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# Benchmark and Near-Benchmark Chernozems: Assessing Human-Induced Transformation and Pedodiversity for Black Soils Conservation

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**ABSTRACT**

The conservation and restoration of black soils (Chernozems) require reliable benchmarks of their natural state to assess anthropogenic transformation. In the old-developed forest-steppe of the Central Russian Upland, this is challenging due to near-total agricultural development. This study evaluates morphological features (horizon thickness, structure, carbonate formations), physical characteristics (bulk density, texture), and chemical parameters (organic and inorganic carbon stocks) of Chernozems, along with soil cover patterns, across three distinct land-use types: a) protected benchmark soils; b) never-ploughed hayfields and pastures (near-benchmark); and c) long-term arable lands.

Our research focused on the Central Russian Upland within the Belgorod oblast, under a moderate continental climate. The soils formed on loess-like carbonate loams and clays on flat interfluves. We analyzed 41 full-profile soil pits to assess soil transformation: 11 in reserves, 18 in never-ploughed hayfields and pastures, and 12 in arable lands. The never-ploughed sites have remained undisturbed for at least 240 years, based on historical map analysis since 1783, while the arable soils have been cultivated for over 120 years. Large-scale soil mapping covered never-ploughed plots ranging from 0.1 to 0.25 ha.

Long-term ploughing leads to soil degradation: compaction in a plough pan at 20–30 cm depth, a substantial reduction in organic carbon stocks (240.4 t/ha in arable soils vs. 316.5 t/ha in benchmarks, 0–100 cm layer), and upward migration of pedogenic carbonates. Soils under hayfields and pastures also show increased bulk density in the upper horizons compared to protected benchmarks, due to animals trampling. However, they show no statistically significant differences in total organic carbon stocks, key morphological properties, soil texture, confirming their high value as near-benchmark References.

The spatial pattern of the soil cover on watershed plains appears similar across reserves, hayfield-pastures, and arable land. However, the component composition differs fundamentally. The never-ploughed sites lack the eroded soil varieties that are widespread on arable land. Under the Russian classification system, a 50x50 m area typically contains 10-20 patches belonging to 5-14 taxonomic groups. In contrast, the WRB system generalizes these same areas into only 3-4 patches and 2 taxonomic groups, highlighting a significant divergence in classification approaches.

Never-ploughed Chernozems in hayfields and pastures are vital for monitoring soil quality, reconstructing pre-industrial soil geographies, and developing sustainable land-use strategies. Their preservation is essential for halting black soil degradation and promoting their role in carbon sequestration.

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# Organic Carbon Loss Process of Black Soil During Cultivation

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## ABSTRACT

Black soils (Mollisols) with abundant organic matter (SOM) and high productivity in Northeast China play a crucial role in national food security and climate change mitigation. However, the content of SOM in this region showed a continuous decline since cultivation, introducing a potential threat to the quality of agricultural soils. In this study, black soils along a 100-year cultivation chronosequence were collected in Baoqing county, Heilongjiang province, China, to assess changes in the content and composition of SOM. Employing soil aggregate and density fractionation schemes and biomarker techniques, shifts in the mechanisms of SOM generation and stabilization were elucidated. The SOM content declined by 43% during the first 30 years of agricultural use, with a rate of 0.74 g C $kg^{-1}$ $year^{-1}$, while reduced by 60% with a rate of 0.31 g C $kg^{-1}$ $year^{-1}$ after 100 years of conversion from the marsh into upland field. Meanwhile, 100-year cultivation resulted in 68% and 19% decreases in the contents of total nitrogen and phosphorus, respectively, and lowered the mean weight diameter of soil aggregates from 4.2 to 1.2 mm. The depletion of soil nutrients and disruption of aggregate structure aggravated the environments for microbes, subsequently weakening soil extracellular enzymatic activities with a cascading consequence of declining soil quality. Biomarkers (lignins, alkanoic acids and amino sugars) were used to evaluate the relative contributions of plant- and microbial-derived C to SOM. With SOM decreasing from ~50 g C $kg^{-1}$ to ~20 g C $kg^{-1}$, the absolute content of plant-derived C decreased by approximately two-thirds, and in contrast, the content f microbial-derived C did not change significantly, which increased its contribution to SOM from 14% to 31%. The microbial-derived C accumulated mainly due to two processes. First, the increase of soil aeration promoted the aerobic microbial metabolisms and increased microbial biomass by 2.7 times, which in turn increased microbial carbon use efficiency from 0.11 to 0.29 and produced more microbial residues. Second, the generated microbial residues could have associated with soil minerals, as reflected by a three-fold increase in the contribution of microbial-derived C in mineral-associated OM (MAOM), which facilitated the maintenance of microbial necromass. The proportion of MAOM in SOM decreased from 85.6% to 72.8%. Meanwhile, the relative abundance of chemically active methoxyl and O-alkly carbon in particulate OM (POM) increased by nearly 100%. This indicated that with the decrease of mineral protection and increase of POM biochemical reactivity, the SOM stability decreased significantly along with its decreasing content. When the SOM content decreased from 50 to 20 g C $kg^{-1}$, dissolved organic matter (DOM) concentration declined by 68.6%, and in contrast, the biodegradability of DOM significantly increased. Spectroscopic analysis revealed that with the decrease in DOM concentration, its aromatic index escalated from 4.33 to 16.8, and spectral slope, indicative of the inverse of average molecular weight, increased from 0.56 to 1.41, and the fraction of protein-like components increased from 6.28% to 38.6%. These shifts suggested that the decline in complex polymers, coupled with the rise of small molecular weight aromatic substances and protein-like components, was the primary factors enhancing DOM bioavailability in black soils. Although SOM could be the main source of DOM, both composition exhibited to be decoupled. The increase in oxygen availability was identified as the main factor influencing the dynamics of DOM composition and bioavailability. As DOM concentration declined, the increased oxygen availability reduced DOM quality. The oxygen-induced oxidation of ferrous to ferric iron removed complex DOM compounds with large molecular weight. And, increased oxygen availability also stimulated oxidase-catalyzed depolymerization of aromatic substances, and promoted production of protein-like DOM components due to lower enzymatic C/N acquisition ratio. This study reveals that patterns of DOM dynamics in black soils are driven by oxygen availability, which extends results from tropical rainforests and wetlands to upland soils with great potential to be managed for soil C sequestration.

**Key words:** Black soils, Dissolved organic matter, Long-term cultivation, microbial necromass, soil organic matter stability

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# Effects of incorporated straw length on runoff and soil loss from black soil under simulated heavy rainfall

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## ABSTRACT

Straw incorporation has been demonstrated an effective measure for soil and water conservation worldwide. Most endeavors have been devoted to evaluate the impact of incorporation rate on soil erosion, yet few attempts have been made to examine the influence of straw size. To fill this gap, rainfall simulation experiments were performed on a typical black soil collected in northeast China, which was packed in runoff plots and incorporated with the maize straw segments of four different lengths, i.e., 2, 5, 10 and 20 cm, at a constant rate of 6 t/hm$^2$. In the meanwhile, a bare black soil without straw incorporation was also subjected to the simulated rainfall, which was used as the control (CK). Designing two slope gradients of 3° and 6°, and two rainfall intensities of 60 and 90 mm/h, the impact of straw length on runoff initiation time, surface flow velocity, runoff depth, sediment concentration and sediment yield were analyzed. The results showed that in contrast to CK, straw incorporation generally delayed runoff initiation and reduced surface runoff. As the straw length increased, moreover, the runoff initiation time increased overall, and the runoff depth declined exponentially. Incorporating the straw segments with the maximum length of 20 cm, the runoff initiation time delayed by 2.8-9.5 times and the runoff depth decreased by 20.8%-37.2% compared to CK. With the increase of straw length, the surface flow velocities on the upper and lower slope sections both decreased initially and then increased, and reached their minima at the medium lengths of 5 and 10 cm. In contrast to CK, specifically, the flow velocities measured on the upper slope decreased by 18.5%-37.4% and 20.1-47.0%, and those on the lower slope section decreased by 35.9%-51.6% and 36.1%-51.6%, respectively. The sediment yields measured at each straw incorporation treatment were lower than those at CK on the whole. Similar with flow velocity, the sediment yield also exhibited decreasing-then-increasing trends with straw length. The sediment reduction benefits were generally the highest when incorporating 5 and 10 cm long straws. The corresponding sediment yields were 19.7%-69.1% and 14.2%-52.1% lower than those at CK, respectively. Nevertheless, the sediment reduction benefit of straw incorporation generally decreased as the rainfall intensity, slope gradient or both increased. Straw incorporation in general delayed runoff initiation, reduced surface runoff, lowered surface flow velocity and impaired soil erosion. However, the responses of runoff and erosion characteristics to incorporated straw length were not consistent. Considering runoff reduction, the application of the 20 cm long straw segments is recommended, which has been found to possess the highest benefits. From the perspective of sediment reduction, in contrast, it is suggested to incorporate the medium-sized straw segments of 5 and 10 cm long, which have been demonstrated the strongest in containing erosion.

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# Integrated Assessment of Slope Erosion in the Mollisol Region of Northeast China Using $^{137}$Cs Tracing and Improved RUSLE2 model

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**ABSTRACT**

The Mollisol region in Northeast China faces severe soil erosion on sloping farmland due to long-term intensive cultivation and complex terrain. This study integrates two research efforts to assess soil erosion and model performance across three slope shapes (straight, convex, and concave) in Heilongjiang Province. An integrated modeling framework combining field observations and artificial intelligence is developed to improve erosion prediction.

In the first part, $^{137}$Cs tracing and wavelet analysis were used to quantify soil erosion-deposition rates and their periodic characteristics across different slope shapes. Significant differences in erosion intensity were found: convex (2009 $t \cdot km^{-2} \cdot a^{-1}$) > straight (1466) > concave (1234). Dominant fluctuation periods were 45.1 m for straight, 55.0 m for convex, and 40.4 m for concave slopes, indicating the strong impact of slope shape on erosion patterns.

In the second part, the RUSLE2 model was enhanced by incorporating random forest regression to integrate slope shape correction factors and slope length parameters. The optimized model improved predictive accuracy, especially for concave slopes ($R^2$ = 0.985, RMSE = 160.2 $t \cdot km^{-2} \cdot a^{-1}$, AVE = 6.32%), demonstrating its effectiveness for erosion prediction in complex terrain.

This study provides a framework combining field data and machine learning to assess slope erosion, revealing spatial heterogeneity and supporting erosion risk zone identification, soil conservation optimization, and Mollisol protection.

**Key words:** Mollisol region, Soil erosion, RUSLE2 model, Machine learning

**Acknowledgments**

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# Straw return combined with fertility enhances soil organic carbon and soil aggregate formation in Mollisol soils

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**ABSTRACT**

Straw return is a widely adopted agronomic practice across the world for enhancing soil organic carbon (SOC), which plays a crucial role in mitigating climate change and promoting sustainable agricultural. However, the effect of pelletized straw, a novel type of straw, on SOC dynamics and soil aggregation is insufficiently studied. Furthermore, the performance of different straw types on SOC pools under varying chemical fertility levels remains unclear. Thus, a field experiment was conducted in a typical Mollisol region of China to quantify effects of straw return types with chemical fertility application levels on SOC fractions and aggregate characteristics. The experiment includes 12 field treatments that combined three straw return types (chopped straw, ST, straw biochar, BC, pelletized straw, PST), and no-straw control (S0) under three chemical fertility levels (80%, 100%, and 120% of recommended fertilization). The results revealed that the ST, BC and PST significantly increased the SOC content by 10.7%, 41.8% and 14.8%, respectively, compared to the S0 treatment. More than 90% of SOC was stored in the form of mineral-associated organic carbon (MAOC) and heavy fraction organic carbon (HFOC). Among the three straw types, biochar application exerted remarkable effects in enhancing the content of SOC and its fractions. Relative to the S0, all straw return types increased the proportion of POC and LFOC, indicating a shift toward more labile carbon. Furthermore, straw return improved soil aggregation by increasing aggregate-associated carbon and elevating the macroaggregate fraction (> 0.25 mm), ultimately enhancing mean weight diameter (MWD) and soil structural stability (SSI). In terms of fertility, increasing fertility application alone enhanced SOC content and stocks while the trend gradually weakened, but it negatively influenced aggregate stability. In contrast, when fertility application combined with straw return, higher fertility level resulted in greater the MWD and SSI values. In summary, these results highlight the critical role of straw return in promoting the storage capacity and stability of soil aggregate. Pelletized straw and biochar could be considered as promising strategies for SOC sequestration in the Chinese Mollisol region.

**Keywords:** Straw return; Soil organic carbon; Pelletized straw; Soil aggregate; Mollisol region

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# Assessing Black Soil Health and Ecosystem Functioning Change in Response to Agricultural Practices in Foumbot, Western Cameroon

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**ABSTRACT**

Andosols, a typical tropical black soil of Cameroon are country's food basket and a sink for carbon storage. These soils are very fertile and intensively cultivated under various agricultural practices. However, little is known about the effect of these agricultural practices on andosol health and ecosystem functioning. To assess this, composite samples were taken at a depth of 0-25 cm, in seven soils cultivated under various agricultural practices (AgP) which include fallow (FA), crop rotation (CR), burning farm (BF) crop association (CA), non-tillage (NT) coffee plantation (CP) and conventional tillage (CT). After performing the physicochemical analyses, we have asses the soil health index as well as ecosystem functioning. The results showed a variation in physicochemical properties depending on the different AgP. Crop rotation improved total nitrogen by 61.1% while tillage degraded it by 27% compared to fallow. Burned farm and tillage degraded organic carbon by 15.25 and 47.8% compared to fallow. SOC, pH, K and silt were identified as key indicators of soil health in the four ecosystem services considered for this study. According to soil health index and ecosystem multifunctionality (EMFs), the following agricultural practices including CR, CA and NT were found to be the one maintaining soil health with SHIs very close to fallow while BF and CT were found to be degrading with SHIs lower by 32.2% compared to fallow. These two practices also decreased ecosystem multifunctionality by 12.85% while CR improved it by 22.7% compared to fallow. Ecosystem functions including nutrient cycling (NC) and physical structural stability (PSS) showed a positive response to the improvement of soil health while carbon cycle (CC) and buffering and filtering capacity (BFC) showed a moderate response. This study highlights the effects of tillage and burning on the degradation of soil health and ecosystem multifunctionality and the conservative role of crop rotation, crop association and non-tillage. These results will help to improve the sustainable management of black soils in the locality of Foumbot.

**Key words:** Agricultural practices, Soil health, Ecosystem multifunctionality, Black soils, Andosols, West Cameroon

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# Long-Term No-tillage Retains Intact Biopores in the Topsoil Compared to Conventional Tillage Based on the Soil Profile Study

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**ABSTRACT**

Soil structure controls various important soil properties and processes and is shaped by the interaction of different organisms (plants, soil fauna and microbes). Biopores, which are caused by growing roots or burrowing earthworms, can extend along the entire soil profile. They are cylindrical in shape and demonstrate low tortuosity and high vertical continuity. They significantly affect infiltration and preferential flow phenomena. In North-east China, earthworms have been shown to prefer the surface layer. Thus, biopores in the deep soil caused by roots are significant. However, how the root system develops under long-term no-tillage is still debated. Some studies suggest that it grows deeper, while others suggest that it accumulates in the surface layer. This study quantifies macro-pore and biopore characteristics under no-tillage (NT) and conventional tillage (CT) treatments, investigating how tillage practices influence vertical pore distribution. Based on a soil profile study in Lishu County, Jilin Province, undisturbed soil columns were collected and analyzed using X-CT scanning. Results show that no significant differences were observed in macro-porosity and pore connectivity across the entire soil profile between CT and NT, except at 40–50 cm depth where NT exhibited higher pore connectivity. At a soil depth of 10–30 cm, NT exhibited a significantly higher number of biopores, with these biopores displaying a greater length compared to CT. The fallow treatment exhibited low macro-porosity and bioporosity, attributable to an absence of tillage and plant roots.

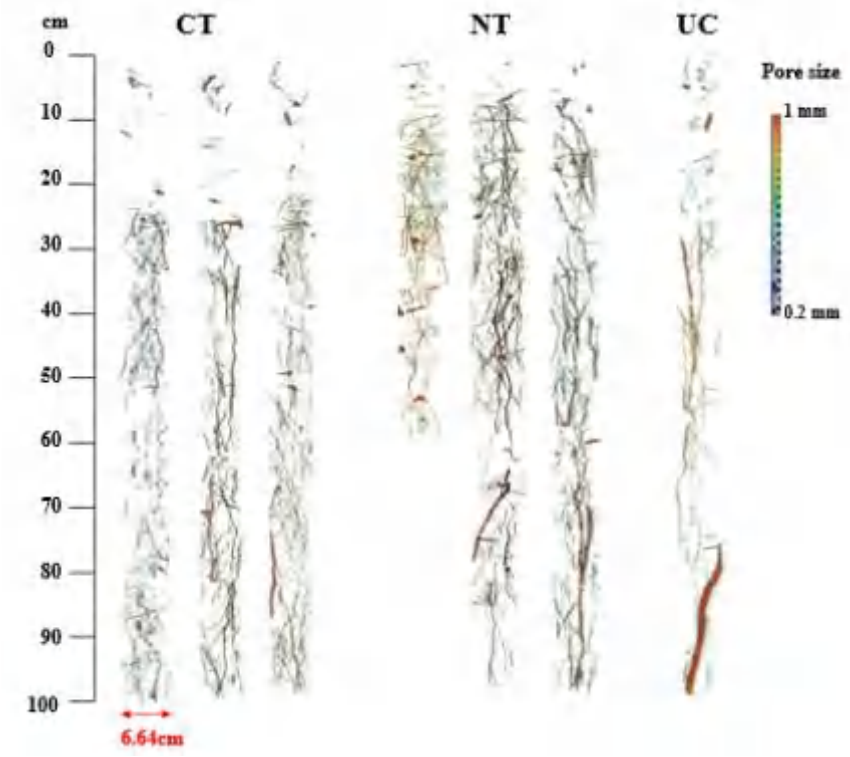



**Fig. 1**. 3D bio-pore networks of continuous 1-meter soil cores under conventional tillage (CT), no-tillage (NT) and uncultivated control (UC).

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# A Comprehensive Framework for Assessing Land Degradation Neutrality in Northeast China's Black Soil Region: Multi-Source Fusion, Driver Analysis, and Scenario Prediction

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**ABSTRACT**

Black soil is among the world's most valuable soil resources, yet only four major black soil regions exist globally, including one in Northeast China. Long-term intensive cultivation has led to widespread erosion and degradation, making the identification of degradation hotspots essential for effective restoration. The land degradation neutrality (LDN) framework proposed by the United Nations Convention to Combat Desertification (UNCCD) offers a key pathway for curbing degradation and supporting sustainable development. Accurate evaluation of land degradation is therefore critical for safeguarding food security and sustaining ecosystem services in this region. In this study, we developed a zoning-based decision fusion rule using consistency analysis and produced six phases of fused land use/land cover (LULC) datasets for 1995–2020. We conducted uncertainty analysis for land productivity (LP) assessments within the LDN framework, established a multi-source data fusion method, and further proposed a Land Degradation Neutrality Index (LDNI). Structural equation modeling was employed to quantify degradation drivers and to predict land degradation trends for 2030. The fused LULC datasets improved mapping accuracy by up to 31.64%, with Kappa coefficients increasing by up to 0.43. Forest-to-cropland conversion, farmland abandonment, and urban expansion were the key contributors to LULC-indicated degradation. Multi-source fusion substantially reduced LP assessment uncertainty, with maximum reductions of 65% in the baseline period and 82% in the assessment period. Degraded and improved land areas were $17.79\times10^4$ km² and $13.32\times10^4$ km², respectively, indicating that the region has not yet achieved LDN. Moreover, 66.6% of physiographic regions, 62.5% of cities, and 69.4% of counties failed to meet the LDN target. Functional disparities were evident: LDNI values for food production land ranged from –0.90 to 0.00, while those for ecosystem service land ranged from –0.32 to 0.38, suggesting higher LDN achievement in ecological land. Socioeconomic factors dominated LDN outcomes. Population exerted strong positive direct effects on both ESF_LDNI and FPF_LDNI (0.890 and 0.601), whereas GDP showed significant negative effects (–0.715 and –0.759). Among the nine future LULC scenarios combining three development pathways and three climate trajectories, the cropland-protection-plus-ecological-conservation scenario consistently produced the greatest improvements and the least degradation, especially under warming and drought-intensified conditions. Overall, this study presents a comprehensive LDN assessment for Northeast China's black soil region using multi-source fused datasets. The integration of driver analysis and scenario simulations provides crucial evidence to support black soil conservation and regional sustainable development.

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# Interspecific interactions increase soil aggregate stability through altered root traits in long-term legume/maize intercropping

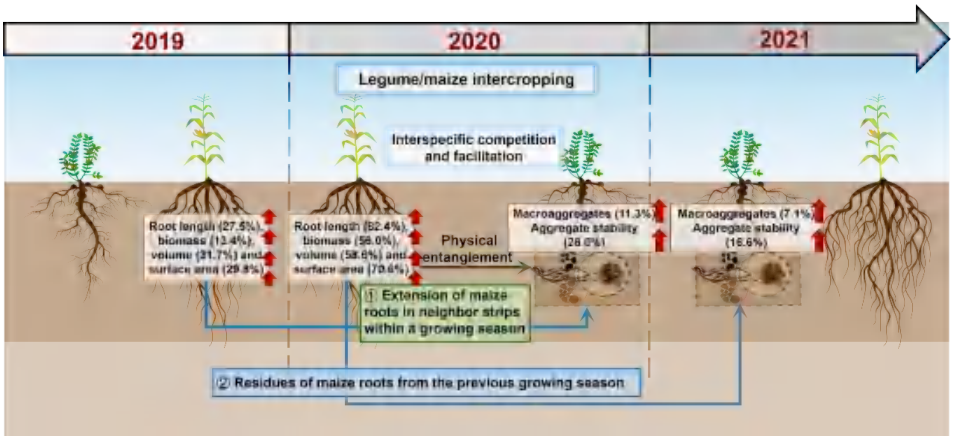
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## ABSTRACT

Species-diverse intercropping systems are associated with increases in soil aggregation but the underlying root mechanisms responsible for greater soil aggregation remain poorly understood. A three-year-long field study was conducted comprising two nitrogen (N) and phosphorus (P) application rates (with and without N or P), and five cropping systems: two maize-based intercropping systems (with peanut or soybean) and their corresponding monocultures (peanut, soybean and maize). Water-stable aggregates and six crop root traits were measured in both monoculture and intercropping. At the plot scale the percentage of soil macroaggregates ($R_{0.25}$), mean weight diameter (MWD), root length density (RLD), biomass density (RMD), volume (RV), and total surface area (RS) had significantly higher values in legume/maize intercropping and maize monoculture than in legume monoculture. At the field-strip scale, intercropping increased the $R_{0.25}$ and MWD of legume strips by 6.4-13.3% and 13.9-31.9% compared to the corresponding legume monocultures. This was induced by the synergistic effects of maize root residues from the previous growing season and the spatial extension of maize roots in the current growing season. Maize roots affected the soil aggregate stability of neighboring soybean and peanut strips in different ways. Intercropping promoted soil aggregation of neighboring soybean strips mainly via maize root traits within the growing season. In contrast, intercropping promoted soil aggregation of the same peanut strips mainly via pre-maize root traits. The results indicate that intercropping can promote soil aggregation, especially in the legume strips of the intercropping system, through interspecific maize-legume interactions that determine changes in root traits. These results provide critical insights into the underlying ecological processes that promote the sustainability of species-rich agricultural systems on mollisols.

**Keyword:** Intercropping; Interspecific interactions; Mollisols; Root residues; Root traits; Soil aggregate stability




**Acknowledgments**

This study was funded by the National Key Research and Development Program of China (2022YFD1500700 and 2022YFC3501503), the National Natural Science Foundation of China (32371627 and 31971450), and the 2115 Talent Development Program of China Agricultural University.

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# Effects of conservation tillage combined with diversified cropping on crop productivity and soil fertility in black soil region

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**ABSTRACT**

The Black Soil Region, renowned for its high fertility, is a crucial grain production base. However, long-term conventional monoculture practices have led to soil degradation, threatening sustainable crop production. Therefore, to investigate the effects of integrating conservation tillage with diversified cropping on crop productivity and soil fertility, a long-term field (2021– ) study was conducted comprising two tillage (CT: conventional tillage; CST: conservation tillage), and five cropping systems (M: Maize monoculture; S: Soybean monoculture; M/S: Maize/soybean intercropping; M-S: Maize-soybean rotation; M-M-S: Maize-maize-soybean rotation). Grain yield, grain mineral concentrations, soil physicochemical properties, soil enzyme activities were assessed. Over the four-year study, CT-M/S and CST-M/S saved 18.37% and 4.38% of land, respectively. M/S increased maize yield by 52.38% but a 37.34% decrease soybean yield compared to their respective continuous cropping systems, and achieved higher temporal stability. Additionally, CST not only increased maize grain yield by 6.62%, but also significantly enhanced the concentrations of Fe and Mn in soybean grains by 6.55% and 29.38%, respectively, compared to CT. Moreover, CST improved soil structural stability and biochemical properties in the 0–5 cm layer, increasing soil organic carbon (SOC) and hemicellulase (BX) activity by 26.6% and 82.5%, respectively, when compared to CT. In the 0-5 cm soil layer, M-M-S significantly increased SOC compared with M and S, with increases of 34.01% and 34.73%, respectively. In the 5-15 cm soil layer, M/S significantly increased SOC compared with M and S, with increases of 19.18% and 17.74%, respectively. The integration of conservation tillage and crop diversification in the Black Soil Region by simultaneously stabilizing grain yield, improving grain quality, and enhancing soil fertility.

**Keywords:** Intercropping, Rotation, Productivity, Soil fertility, Black soil

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# The overlooked plant litter in the long-term biodiversity experiments

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**ABSTRACT**

Plant biodiversity–productivity relationships become stronger over time in grasslands, forests and agroecosystems. Plant shoot- and root-litter is important in mediating these positive relationships, yet the functional role of plant-litter remains overlooked in long-term experiments. We propose that plant-litter strengthens biodiversity-ecosystem functioning relationships over time in four ways by: (i) providing decomposing detritus that releases N through time for uptake by existing and succeeding plants, (ii) overall enhancing soil fertility, (iii) changing soil community composition, and (iv) reducing the impact of residue-borne pathogens. We bring new insights into how diversity–productivity relationships may change over time and suggest that the diversification of crop residue retention through increased residue diversity from plant mixtures will improve the sustainability of food-production systems.

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# Soil Erosion Processes and Dynamic Mechanisms under Soil Compaction and Freeze-Thaw Cycles in the Black Soil Region of Northeast China

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**ABSTRACT**

Soil erosion resulting from the interaction between soil compaction and seasonal freeze-thaw (FT) cycles is a critical environmental issue in the intensive agricultural black soil region of Northeast China. While FT cycles are recognized for their potential to alleviate soil compaction, the cross-temporal mechanisms connecting pre-FT compaction-induced microstructural evolution to post-FT erosion dynamics remain poorly understood. This study integrated in situ field erosion experiments with X-ray computed tomography (CT) scanning to comparatively analyze soil properties, pore structure characteristics, and erosion responses under varying compaction levels before and after the seasonal FT period. Results indicated that prior to the FT period, soil compaction significantly increased bulk density and reduced porosity, creating a dense, layered microstructure with diminished pore connectivity and fractal dimension. This structural degradation led to a significant increase in total runoff and sediment mass, driven primarily by enhanced runoff scouring capabilities. Following the seasonal FT period, CT visualization revealed that FT cycles functioned as a natural restorative mechanism, significantly increasing total pore number, connectivity, and porosity in compacted soils. However, this physical recovery came at the cost of structural stability; FT cycles disrupted soil aggregates, leading to a significant decline in water-stable aggregate stability and shear strength. Consequently, while sediment mass in compacted soils decreased by 1.84%–57.73% post-FT compared to pre-FT levels due to improved infiltration, it remained 28.59%–148.22% higher than in uncompacted soils. Structural Equation Modeling (SEM) revealed a shift in erosion mechanisms: whereas pre-FT erosion was dominated by compaction-induced runoff, post-FT erosion was driven by the synergistic interaction between residual runoff scouring and reduced soil erosion resistance caused by microstructural fragmentation. These findings highlight that pre-FT compaction exacerbates spring erosion risks through legacy effects on soil microstructure, emphasizing the need for soil management strategies that mitigate compaction prior to the freezing season.

**Keywords:** Black Soil; Soil compaction; Freeze-thaw cycles; Soil erosion process; Soil structure

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# Intercropping, soil microbiomes, and mycotoxin risk: mechanistic pathways for safer maize production

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**ABSTRACT**

Climate change has intensified fungal contamination in maize, leading to higher mycotoxin burdens and increasing risks to food safety and human health. Intercropping, as a biodiversity-based agroecosystem practice, is known to enhance ecological functioning and reduce disease pressure. Because *Fusarium* ear rot is a soil-borne disease closely linked to soil conditions in Northeast, soil may play a key role in regulating mycotoxin accumulation. However, the extent to which intercropping mitigates mycotoxin risks through changes in soil microbial communities remains unresolved. To address this question, we quantified maize kernel mycotoxins in 2024 under three cropping systems (maize monoculture, maize/peanut intercropping, and maize/soybean intercropping) and conducted metagenomic analyses of rhizosphere soils sampled at the jointing stage. We formulated two hypotheses: (i) intercropping reduces mycotoxin accumulation relative to monoculture; and (ii) this reduction is driven by shifts in rhizosphere microbial communities, particularly by increases in beneficial microbial taxa and decreases in pathogenic fungi associated with toxin biosynthesis. By integrating field mycotoxin measurements with rhizosphere metagenomic profiling, our study provides a mechanistic basis for understanding how intercropping-mediated microbial regulation can lower mycotoxin risks and contribute to more resilient maize production systems.

**Keywords:** Intercropping, Black soil, Mycotoxin, Soil microbiomes

**Acknowledgments**

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# Multi-platform monitoring method for the quality of Black soils cropland and site specific application

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**ABSTRACT**

Recently, quantitative monitoring indicator systems and technical systems adapted to the resource characteristics of black soils cropland are lacking, leading to unclear baselines and dynamics of black soils quality and limiting the ability of existing assessments to accurately guide protection and utilization technologies. This study establishes a cropland system theory, analyzing relationships among system elements, structure, processes, and functions, and constructs a quantitative monitoring indicator system. An integrated multi-platform monitoring system suitable for black soil characteristics was created to obtain multi-scale datasets of key cropland quality elements for black soils, including both soil elements (soil organic matter (SOM), thickness of the black soil layer, texture, etc.) and utilization and productivity elements (field boundaries, ditches, forests, roads, and crop planting structure, etc.). This enables multi-temporal quantitative monitoring of SOM from field scale to Northeast China and to the world's four major black soils regions, as well as precise monitoring of spatial variation patterns of SOM and other elements within individual fields. The quantitative monitoring results have been extensively applied in the Beidahuang Group, constructing spatiotemporal big data that guides precision protection and utilization of black soils through prescription maps for variable-rate fertilizer applicators, subsurface drainage pipe installation machinery, and other equipment.

**Acknowledgments**

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# Mechanistic Insights into Cover Crops and Straw Incorporation: Root Traits, Soil Properties and Carbon Controls on Erosion Resistance across Degradation Gradients in Mollisols

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**ABSTRACT**

Soil erosion is a primary driver of Mollisol degradation, yet the mechanisms through which cover crops and straw incorporation regulate erosion resistance across degradation gradients remain unclear. Here, straw incorporation, cover crops (winter wheat, ryegrass, hairy vetch, and a ryegrass–vetch mixture), and their combinations were tested under simulated slight, moderate, and severe degradation, using maize monoculture as the control (CK). Erosion resistance was jointly evaluated using aggregate stability (erodibility resistance) and detachment capacity (detachment resistance), while dominant drivers were identified using random forest and partial least squares path modeling. All treatments improved erosion resistance relative to CK. Grass cover crops enhanced soil erodibility resistance by 2%–22% under slight to moderate degradation and increased detachment resistance by 20%–310% across all gradients, both relative to straw. Under severe degradation, however, legume cover crops exhibited 8%–32% higher erodibility resistance than both straw and grasses. Moreover, cover crop–straw integration exhibited complementary effects on erosion resistance under slight to moderate degradation, but provided no additional advantage over cover crops alone under severe degradation. Root traits emerged as the primary drivers, exerting direct control over detachment resistance, while their influence on erodibility shifted from indirect (via soil properties and carbon) under slight degradation to direct under moderate–severe degradation. As degradation severely intensified, soil properties and organic carbon fractions gained stronger direct effects on soil erosion resistance. These degradation-dependent shifts reveal how root–soil–carbon interactions reorganize erosion resistance, providing mechanistic insights for adaptive conservation strategies in Mollisol regions and other erosion-prone agroecosystems worldwide.

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# Bio-tillage: A new perspective for sustainable agriculture

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**ABSTRACT**

For sustainable agriculture production, we proposed bio-tillage in this paper, which is defined as improving soil structure with plant roots for boosting growth of crops. Cover crops with thick and deep roots can be used for bio-tillage since they can effectively improve soil structure, water and air conductivity by forming biopores (root channels) which provide space with least resistance, high oxygen and nutrients to promote root growth. The effect of bio-tillage on crop yields varies with climate conditions and management practices. The effective bio-tillage cover crop should have thick and deep roots, rapid root growth rates and rapid decomposition of remnant roots, and good adaption to climate and soil constraints. Planting cover crops timely and killing at suitable stage with a roller-crimper can benefit bio-tillage. The limited understanding of ideal biopore architecture for root growth, more effective bio-tillage cover crop species, and field management of bio-tillage, requires to be addressed before widely application of bio-tillage.

**Key words:** Bio-tillage; plant roots; cover crop; biopores; sustainable agriculture

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# The impact of cover crops on the active components of organic carbon in black soil after straw return to the field

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**ABSTRACT**

Straw returning is generally considered beneficial for maintaining and improving soil organic carbon (SOC). However, the higher carbon- to- nitrogen ratio of straw can induce nitrogen limitation in soil microorganisms, thereby hindering the accumu lation of SOC during straw decomposition. The integration of straw and legume- based cover crops theoretically enhances straw decomposition by fixing nitrogen and optimizing the carbon- to- nitrogen ratio. The greenhouse pot experiments were conducted to evaluate the effects of three legume cover crops (hairy vetch, white clover, and alfalfa) and two grass cover crops (ryegrass and winter wheat) separately in cooperation with straw amendment on the SOC and total nitrogen (TN) content at both bulk soil and aggregate scale. Compared to bare soil (CK), returning straw, planting cover crops alone, or combining straw with grass cover crops all enhanced SOC content, while simultaneously reducing TN content to varying degrees. Straw returning in cooperation with legume cover crops increased both SOC and TN, ranging from 4.40% to 5.51% and 1.38% to 2.81%, respectively. The en hancement of TN content resulting from the combination of straw with legume cover crops was 4.7% and 10.2% greater than that achieved through straw returning alone and combining straw with grasses. The combination of legumes with straw substantially enhanced the SOC and TN content across different aggregate scales, particularly demonstrating optimal results when combined with white clover. Legume cover crops produced a greater volume of root exudates and had coarse root systems that directly en hanced SOC and TN content, while indirectly promoting SOC sequestration by improving TN content. The integration of straw returning with legume cover crops showed significant potential to enhance SOC sequestration and TN fixation. This strategy offers a sustainable agricultural pathway to minimize nitrogen fertilizer usage, facilitate straw decomposition, and effectively elevate both carbon and nitrogen levels in the soil

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# Carbon-rich African dark earths have lower carbon footprint than adjacent land use types

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## ABSTRACT

In West Africa, indigenous soil improvement has resulted in fertile soils known as African dark earths (AfDEs) similar to the Amazonian *Terra preta*. However, there is paucity of information on the biogeochemical processes of such soils. Here, we report soil carbon sequestration in such unique AfDEs in Ghana through assessment of persistent mineral-associated organic carbon (MAOC) and labile particulate organic carbon pools (POC) and quantified the carbon foot print thereof through in-situ greenhouse gas measurements. We also studied the vulnerability of soil organic carbon to decomposition through a 98-day laboratory incubation study. We compared AfDE sites with adjacent non AfDEs cropland including fallow land at stratified soil depths of 0-10, 10-20, and 20-30 cm. Four 20 m × 20 m subplots were demarcated in each land use type. Soil organic carbon pools were measured using the granulometric fractionation methods on Elemental Analyzer Vario Macro cube (Elementar, Germany). AfDE croplands had greater soil organic carbon stock (20.49- 50.91 Mg $ha^{-1}$) than the non-AfDEs (7.82-27.33 Mg $ha^{-1}$) at 0-10 cm depth. Out of these stocks, the cumulative $CO_2$ fluxes ranged from 1.04 ± 0.1 to 1.32 ± 0.18 Mg $CO_2$ $ha^{-1}$ from AfDE croplands and 0.92 ± 0.05 to 1.38 ± 0.01 Mg $CO_2$ $ha^{-1}$ for non-AfDE croplands at the 0-10 cm depth. There were 0.81 ± 0.1 to 1.18 ± 0.10 Mg $CO_2$ $ha^{-1}$ fluxes from non-AfDE fallow, and 1.5 ± 0.06 Mg $CO_2$ $ha^{-1}$ for converted fallow land. Overall, AfDE cropland emitted less $CO_2$ (< 2 %) of the stock and acted as a net sink for $CH_4$ due possibly to its greater persistent MAOC pool (18.06-31.13 mg C $kg^{-1}$ soil) than the non-AfDE croplands (5.41-19.25 mg C $kg^{-1}$ soil) and non-AfDE fallow (5.11-18.36 mg C $kg^{-1}$ soil). This was also confirmed by the low vulnerability of SOC to microbial decomposition as the 98-day soil incubation period showed lower $CO_2$ fluxes for AfDE cropland (118.28 mg $CO_2$ $kg^{-1}$ soil) than non-AfDE fallow (121.54 mg $CO_2$ $kg^{-1}$ soil) and non-AfDE cropland (128.70 mg $CO_2$ $kg^{-1}$ soil). Results showed that more of the soil organic carbon was stabilized in the mineral-associated organic pool (ca. 52.97-87.56 %) with AfDE cropland significantly ($P<0.003$) stabilizing more carbon (ca. 64.78-87.56%) than the non-AfDE cropland. A multivariate analysis showed soil factors *viz*. soil moisture, total N stock, mineral-associated N, sand, and clay, and climatic factors of rainfall, ambient temperature accounting for ca. 62.1 % of the variability in GHG emissions across locations. However, a stepwise regression analysis in linear mixed model showed soil moisture as the principal factor driving (32 %) the emission of greenhouse gases across land use types with less confounding effect from site, N fertilizer application, and management practices. The study provides a first-hand information on drivers of soil carbon sequestration and fluxes from AfDEs to inform climate-resilient decisions.

**Keywords:** Anthropogenic dark earth, African dark earth, carbon footprint, carbon pools, climate change, greenhouse gases.

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# SynCom-Driven Iron Modulation Synergistically Controls Maize Root Rot

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## ABSTRACT

Maize root rot in the northeast black soil region of China is a soil-borne disease caused by *Fusarium graminearum*. Infected plants exhibit characteristic root decay and wilting, causing significant yield reduction. Traditional chemical control faces dual challenges of enhanced pathogen resistance and soil microecological damage. This necessitates eco-friendly biocontrol through rhizosphere microecological regulation. Although rhizosphere microorganisms offer a promising green control strategy, their application is hindered by the scarcity of highly efficient stable strains and insufficient understanding of the synergistic "microbiota-host-pathogen" disease resistance network. Recent studies indicate that the iron metabolism network as a central regulatory hub for tripartite interactions (Verbon et al., 2017). Beyond nutrition, iron regulates disease balance. Iron thus bridges microbial ecology and plant immunity, though its cross-kingdom signaling mechanisms remain undefined.

Here, we employed amplicon sequencing to identify the core antagonistic strain *Lysinibacillus* sp. R104 and the siderophore-producing strain *Pseudomonas chlororaphis* R36, constructing the synthetic microbial community (SynCom) R36+R104. We established both in vitro (SynCom-*F. graminearum*) and in vivo (SynCom-*F. graminearum*-maize) co-culture systems, integrating interaction transcriptomics with root metabolomics, and validating core gene functions through molecular genetic approaches. The SynCom demonstrated dual synergistic disease-suppression mechanisms: (1) Direct antagonism: Enhanced colonization via biofilm formation coupled with $Fe^{3+}$ reduction to $Fe^{2+}$, catalyzing fenton reactions that disrupt *F. graminearum* hyphal membrane integrity; (2) Plant immune synergy: Activation of maize iron deficiency response pathways significantly upregulated iron metabolism genes (*Zmspo3*, *ZmVIT1*, *ZmNramp2*, *Zmprx12*) to optimize rhizosphere iron allocation and stimulate lignin deposition. Root-secreted coumarin glycoside esculin maintains host iron homeostasis through chelation while damaging pathogen membrane structures to enhance resistance. Field applications achieved 65% disease control efficacy and 8.37% maize yield increase. This work elucidates the iron competition-mediated tripartite interaction network, providing a theoretical foundation for developing green microbial agents and technological support for sustainable agriculture.

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# Mechanisms Underlying the Resistance of Rahnella sp. RS86 to Maize Root Rot

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**ABSTRACT**

Maize root rot is a major soil-borne disease threatening global maize production and is primarily caused by multiple fungal pathogens, among which *Fusarium graminearum* (Fg) is considered one of the predominant causal agents during the seedling stage. This disease not only results in poor early plant development and yield losses ranging from 10–30%, and even exceeding 50% under severe conditions, but also leads to the accumulation of mycotoxins such as deoxynivalenol (DON), posing serious risks to livestock health and food safety. Owing to the long-term reliance on chemical fungicides, which has resulted in environmental contamination and increased pathogen resistance, the development of efficient and environmentally friendly biological control agents has become an urgent requirement for sustainable agriculture. In this study, a rhizosphere bacterium with strong biocontrol potential, *Rahnella* sp. RS86, was isolated from maize fields with a high incidence of root rot in Tongyu County, Jilin Province, China.

Experimental results demonstrated that RS86 exhibited significant antagonistic activity against Fg in vitro, with an inhibition rate of 21.92%. In terms of plant growth–promoting traits, RS86 showed strong nutrient transformation capabilities, producing indole-3-acetic acid (IAA) at a high level of 39.61 mg/L, and possessing efficient organic and inorganic phosphate solubilization as well as nitrogen fixation abilities, thereby substantially improving plant nutrient acquisition. Greenhouse experiments revealed that inoculation with RS86 significantly reduced the root disease index of maize by 23.2% at 7 days post-inoculation. Moreover, at 14 days post-inoculation, the shoot fresh weight of maize increased by 46.6% compared with the control, indicating a pronounced early growth-promoting effect. Field trials further confirmed its practical application value, as RS86 treatment significantly increased maize yield by 5.8% under Fg infection pressure, effectively mitigating economic losses caused by the disease. Interaction transcriptome analysis revealed that RS86 modulates root immune responses in maize, alleviates Fg-induced reactive oxygen species (ROS) bursts, enhances antioxidant capacity, activates key defense-related pathways such as MAPK and jasmonic acid (JA) signaling, and promotes cell wall reinforcement and growth-related metabolism, thereby enabling maize plants to maintain growth while enhancing disease resistance.

In conclusion, Rahnella sp. RS86 is a promising biocontrol bacterium that integrates direct antagonistic activity, induced resistance, and systemic plant growth–promoting functions. It not only suppresses pathogen invasion through physical and chemical barriers but also coordinates disease resistance and growth by modulating phytohormone signaling balance. This study provides both a theoretical basis and valuable microbial resources for the development of novel biological control agents against maize root rot and holds important implications for black soil conservation and green agricultural production.

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# Soil fertility and mean annual precipitation regulate the influences of tillage regimes on black soil organic C stocks in Northeast China

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## ABSTRACT

Black soils (Mollisols) are widely recognized for their high soil organic C (SOC) content and agricultural productivity. Northeast China contains approximately 180000 $km^2$ of arable black soil (Sui et al., 2023) and has become a cornerstone for securing national food safety. However, long-term intensive agriculture and serious soil erosion have substantially degraded the quality and productivity of the black soils in Northeast China. Nearly 64% ofcropland in Northeast China experienced a decline in SOC content between 1985 and 2020, with a mean decrease of 3.07 g C $kg^{-1}$ and a C storage reduction of 0.32 Pg (Wang et al., 2023). Therefore, restoring SOC stocks has become an urgent priority for the conservation ofblack soils in Northeast China.
Zero tillage with straw mulching (ZT) is a typical conservation tillage practice that has been widely adopted to reduce soil erosion (Akplo et al., 2022), improve soil structure (Marahatta et al., 2025), and enhance SOC accumulation (Pramanick et al., 2024). However, a 20-year field experiment conducted by Zhang et al. (2023) indicated that ploughing with straw return enhanced SOC sequestration more effectively than ZT in warm and humid regions. In contrast, the meta-analysis by Ul Islam et al. (2023) demonstrated that ZT generally outperformed deep tillage with straw return (DP) in enhancing topsoil SOC stocks under warm and dry climatic conditions. Hermle et al. (2008) reported no significant differences in SOC stocks among deep ploughing, shallow tillage, and zero tillage under moist, cold-temperate climatic conditions. These findings suggest that the interactive effects of climatic conditions and tillage regimes on SOC stocks remain insufficiently understood. Given the vast heterogeneity of climatic and edaphic conditions across the black soil region ofNortheast China, a systematic evaluation of the effects of different tillage regimes on regulating SOC dynamics remains lacking. Here, a six-site networked field experiment was conducted to (1) compare the effects of different tillage regimes on SOC stocks, (2) identify the key environmental drivers of SOC stocks in the black soil region of Northeast China, and (3) examine the influences ofthese key drivers on SOC stocks across tillage regimes.
The networked field experiments were conducted at six sites located in the western semi-arid zone (Qiqihar, QQ; Baicheng, BC; and Chifeng, CF) and the eastern semi-humid zone (Hailun, HL; Gongzhuling, GZL; and Tieling, TL) of the black soil region of Northeast China (Fig. 1). Field experiments were performed following a randomized block design with three replications. Three tillage regimes were consistently implemented at each site: namely, zero tillage with straw mulching (ZT), deep plowing with straw incorporation (DP), and rotary tillage with straw removal (RT). RT is the traditional agricultural practice that has been adopted by the local farmers for decades. Specifically, a rotary tiller was applied twice to a depth of 10-15 cm after straw removal. In the DP treatment, maize straw was chopped twice using a straw rotary cultivator and incorporated into the subsoil by moldboard ploughing to a depth of 30-35 cm. Subsequently, the topsoil was tilled twice using a rotary tiller before sowing the following year. Similarly, soils in the ZT treatment received no tillage throughout the year. Maize straw was chopped following the same procedure as in the DP treatment and directly mulched onto the soil surface. The cropping system at each site was a continuous maize monoculture, with maize sown in May and harvested in October. Soil samples were randomly collected at 0-20 cm and 20-40 cm depths from each experimental plot using a soil auger before maize harvest, which were air-dried and sieved prior to SOC determination. Soil bulk density (BD) was measured by collecting undisturbed soil samples using cutting rings (100 $cm^3$) from the midpoints of the 0-20 cm and 20-40 cm soil layers. To eliminate the effects of tillage-induced soil disturbance, the equivalent soil mass (ESM) method was applied to calculate SOC stocks.



**Fig. 1** Locations of experimental sites and mean annual precipitation (mm) and temperature (°C) across Northeast China. QQ, BC, CF, HL, GZL, and TL stand for Qiqihar, Baicheng, Chifeng, Hailun, Gongzhuling, and Tieling.

Comparing with the traditional tillage regime (RT) adopted by the local farmers, zero tillage with straw mulching (ZT) increased SOC stocks in the 0-40 cm soil profile by 1.5%, 3.1%, 7.1%, and 14.7% in HL, CF, QQ, and GZL, respectively (Fig. 2). Further ANOVA results confirmed that only the SOC accrual in GZL was statistically significant. Deep plowing with straw return (DP) increased the subsoil SOC stock (20-40 cm) by 11.1% compared to RT, resulting in an overall SOC stock increase by 2.7% within the 0-40 cm soil profile (Fig. 2f). In contrast, DP significantly reduced the subsoil SOC stock in CF, leading to an overall SOC stock decrease of 12.8% in the 0-40 cm profile compared with RT (Fig. 2c). Moreover, changes in subsoil SOC stocks induced by different tillage regimes predominantly determined SOC stock dynamics throughout the 0-40 cm soil profile.



**Fig. 2** Soil organic C stocks estimated using the equivalent soil mass (ESM) method across six experimental sites. RT stands for rotary tillage with straw removal, which is the traditional agricultural practice adopted by local farmers. DP and ZT represent deep plowing with straw return and zero tillage with straw mulching, respectively.

Mean annual change rates of topsoil SOC stocks were estimated relative to initial conditions across all six experimental sites (Fig. 3). Results indicated that the influence of regional climatic conditions on SOC stock change rates exceeded that of tillage regimes. SOC stock accruals generally occurred in the semi-arid zone (Fig. 3a-c), whereas reductions in SOC stocks prevailed in the semi-humid zone of the black soil region in Northeast China (Fig. 3d-f). The ZT treatment exhibited a significantly greater resistance to SOC loss compared to RT in GZL, despite the negative mean SOC stock change rate (Fig. 3e). In addition, the rates of SOC stock reduction in HL were substantially higher than those in GZL and TL. This phenomenon is likely related to the high background SOC content in HL (approx. 3%). Linear regression analyses indicated that SOC change rates showed significant negative relationships with mean annual precipitation (MAP) and initial SOC content (Fig. 4a,c), whereas a significant positive linear relationship was observed with mean annual temperature (MAT; Fig. 4b). Furthermore, the estimated SOC change rates were compared among the three tillage regimes. The results showed that ZT was more effective in promoting SOC accumulation in the western semi-arid zone of the black soil region in Northeast China compared to DP and RT (Fig. 4d,e). Overall, by synthesizing results from six long-term field experiments, this study demonstrated that zero tillage has the potential to mitigate SOC loss in the black soil region in Northeast China. However, optimizing tillage regimes alone is insufficient to halt SOC degradation of the black soils in Northeast China, especially those in the semi-humid zone. Additional measures, such as exogenous C inputs, are required to fully restore SOC stocks in this region.



**Fig. 3** Soil organic C stock change rates across the experimental sites. SOC stocks (Mg $ha^{-1}$ $yr^{-1}$) were estimated by the equivalent soil mass method. QQ, BC, CF, HL, GZL, and TL stand for Qiqihar, Baicheng, Chifeng, Hailun, Gongzhuling, and Tieling. RT stands for rotary tillage with straw removal, which is the traditional agricultural practice adopted by local farmers. DP and ZT represent deep plowing with straw return and zero tillage with straw mulching, respectively.



**Fig. 4** Relationships between SOC stock change rates and mean annual precipitation and temperature and initial SOC content. Plot d and e were estimated by the multi-variable linear regression models, where the SOC change rates (SOCs.CR; % $yr^{-1}$) of ZT were subtracted by those of DP and RT respectively.

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# Alleviating Soil Compaction under No-Till Management: Impacts of Cropping System

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**ABSTRACT**

Background: Soil mechanical compaction presents a significant challenge in sustainable agriculture. No-till systems, while beneficial for soil conservation, can exacerbate this issue. The role of different crop species and rotations in mitigating compaction within these systems requires further elucidation.

Methods: A three-year field study (2022-2024) evaluated the effectiveness of four cropping systems under no-till conditions in remediating soil compaction: continuous soybean, continuous maize, soybean-maize rotation, and a diversified maize-forage legume rotation. Soil physical status was assessed via continuous monitoring of soil penetration resistance. Concurrently, crop yield was measured to assess agronomic performance.

Results: The maize-forage legume rotation demonstrated the most significant reduction in soil penetration resistance, indicating the best remediation of soil compaction. Continuous soybean followed as the second most effective system. In contrast, the soybean-maize rotation and continuous maize showed the least improvement in soil physical conditions. Crop yield trends generally aligned with the soil health benefits.

Conclusion: The choice of cropping system profoundly influences soil compaction dynamics under no-till management. Diversified rotations incorporating deep-rooted legumes, such as the maize-forage legume system, offer a superior strategy for mitigating mechanical compaction. The deep root systems of leguminous plants are hypothesized to be a key factor in enhancing soil porosity and structure. These findings highlight the critical importance of strategic crop sequencing, beyond simple no-till adoption, for achieving long-term soil health and productivity.

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# Thermal Stability of Soil Organic Matter in Farmland Chernozems

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**ABSTRACT**

To adapt agriculture to long-term soil organic carbon sequestration, it is crucial to understand the spatial variability and drivers of its stock stability under farming conditions. Thermal techniques are effective tools to measure the intrinsic soil organic matter (SOM) stability, based on the analysis of the energy required to break chemical bonds in organic molecules and organic-mineral associations. This study quantified the spatial variability of thermal stability of SOM in Chernozem topsoil (0–10 cm) across contrasting management systems in a commercial agricultural setting. The study was conducted in the Russian forest-steppe (Samara region; 54.1°N, 50.3°E) capturing fields with conventional tillage (sunflower-wheat-bare fallow) and no-tillage for 5 and 8 years (soybean-sunflower-wheat). To collect 90 soil samples throughout the study area (291 ha), we used a model-based sampling design with a range of terrain covariates (i.e., conditioned Latin Hypercube sampling). The thermogravimetric analysis of the soil was carried out on the TGA/DSC 3+ (Switzerland) with samples heating from 30 to 650 C with rate of 10 C $min^{-1}$. SOM was divided into labile (mass losses at 200-400°C), stable (400-460°C), and persistent (460-600°C) pools. SOM stability was assessed using two integral indicators: the temperature at which half of the SOM is lost ($T_{50}$) and the ratio of the sum of the stable and persistent pools to the labile pool ($K_{stab}$). Across the study farmland area, the SOM content varied from 65 to 130 mg $g^{-1}$, half of which was the thermally labile pool (50-59%). The remaining half of the SOM was almost equally formed stable (17-22%) and persistent (20-33%) pools. No significant differences in the SOM stability were found between the management systems used. Concurrently, the lower the SOM content, the higher $T_{50}$ and $K_{stab}$ values (Pearson's correlation coefficient: $r$ = –0.74-0.72 at $P$-value <0.001). SOM thermal stability ($T_{50}$ and $K_{stab}$) increased with carbonate content ($r$ = 0.69–0.72, $P$ <0.001). At the same time, an inverse trend was found between the SOM stability ($T_{50}$ and $K_{stab}$) and soil microbial biomass content ($r$ = –0.30-0.33, $P$ <0.01). These findings emphasize that an increase in SOM thermal stability in Chernozems is associated with depleted SOM stocks and deteriorating nutrient availability. Therefore, the strategy for restoring soil fertility in farmlands should aim to boost the thermally labile pool, as it actively contributes to biochemical nutrient cycling.

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# Short-term effects of overwintering on porosity of the compacted topsoil due to harvest traffic in Northeast China

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## ABSTRACT

The multi-hydrothermal processes in agricultural soils during overwintering modify compacted soil structure in cold winter regions. The depth-dependent changes in the topsoil pore-network within field-based compacted zones caused by harvest traffic, before and after winter, remain poorly understood. In this study, we aimed to investigate the short-term effects of overwintering on topsoil porosity of a clay loam soil in the harvest traffic zone in Northeast China using X-ray CT. Undisturbed soil cores were collected in the 0-10 cm layer of the non-traffic and traffic zones before and after winter. After harvest, both total porosity ($\varepsilon_{total}$) and porosity of > 0.04 mm ($\varepsilon_{X\text{-}ray}$) significantly decreased by 0.04 and 0.07 $cm^3$ $cm^{-3}$ due to the machinery traffic, respectively. Following winter, the $\varepsilon_{total}$ of the traffic zone significantly increased by 0.08 $cm^3$ $cm^{-3}$ and was greater than that of non-traffic zone porosity before winter. The loosening effects of overwintering on compacted soil in the traffic zone diminished with increasing soil depth, and marked alterations limited to the uppermost 3.5 cm. The increase in $\varepsilon_{X\text{-}ray}$ was primarily resulted from the changes in 0.04-1.0 mm pores. Therefore, it is indicated that overwintering can alleviate soil compaction of traffic zone only in the uppermost layer.

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# Long-term no-tillage farming mitigates waterlogging during extreme rainfall events in black soil region of NE China

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**ABSTRACT**

The increasing frequency of extreme rainfall events intensifies waterlogging-induced aeration stress on crops, highlighting the urgency for adaptive agricultural practices. This study evaluates the potential of long-term no-tillage (NT) farming to mitigate waterlogging risks on a silty clay loam in Northeast China by comparing with traditional moldboard plough (MP) farming using an 11-year field experiment. Rainfall simulation (40 mm $h^{-1}$) and dye-tracing were employed to study the dynamics water infiltration, and X-ray computed tomography (CT) was applied to examine soil pore characteristics (0–60 cm depth) and their responses (0–5 cm layer) to raindrop splashing. Results demonstrated that NT significantly enhanced water infiltration capacity, with a 161% higher maximum infiltration depth (*MID*), an 65% increase in total stained area (*TSA*), and 95% less surface ponding compared to MP. Although MP exhibited higher total porosity ($\varepsilon_{total}$), macroporosity (> 0.04 mm pores, $\varepsilon_{X\text{-}ray}$), and increased pore connectivity in the 0–20 cm layer, it had fewer biopores and greater vertical stratification of macroporosity compared to NT across the 0–60 cm profile. During rainfall events, the MP plot experienced a 28% reduction in porosity of pores sized 0.2–1.0 mm and a 19% increase in porosity of pores < 0.2 mm in the surface layer, likely due to raindrop splashing, while NT maintained pore integrity through straw mulching. We conclude that long-term NT is effective in enhance soil resilience to waterlogging by developing continuous vertical pore networks and maintaining surface mulch, thereby improving climate adaptability in the black soil region of Northeast China.

**Acknowledgments**

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# Drivers of soil quality and maize yield under long-term tillage and straw incorporation in Mollisols

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**ABSTRACT**

Proper tillage combined with straw management is crucial for maintaining agroecosystem sustainability and crop yield, especially under intensified agricultural activities. However, the optimal depth for tillage in combination with straw incorporation remains unclear. To address this, we established a field experiment in 2011 in Mollisols with five treatments: conventional tillage (CT, tillage depth 20 cm), no-tillage combined with straw return (SNT), conventional tillage combined with straw return (SCT), inversion tillage combined with straw return (SIT, tillage depth 35 cm), and subsoil tillage combined with straw return (SST, straw depth 20–35 cm). We assessed the effects of these treatments on soil quality by evaluating the Soil Physical Property Index (SPI), Soil Chemical Property Index (SCI), and Soil Microbial Property Index (SMI) in relation to the Soil Quality Index (SQI) and crop yield. Our findings shown that tillage combined with straw return significantly improved soil properties. Compared to the CT, SNT, and SST treatments, the SCT and SIT treatments increased SPI and SQI in the 0–20 cm soil layer by 43.9–845.4%. While the SIT and SST treatments enhanced SPI, SCI, and SMI in the 20–35 cm soil layer by 69.2–307.7% more than the CT, SNT, and SCT treatments. Among all treatments, SIT treatment resulted in the highest SPI, SCI, and SMI in the 0–35 cm soil layer. Additionally, SQI and maize yield under the SIT treatment were 11.7–140.5% and 15.6–78.0% higher, respectively, compared to other treatments. Linear regression analysis revealed that SPI in all layers had a significant impact on maize yield, while SCI and SMI were significantly correlated with yield only in the 20–35 cm layer ($P < 0.05$). SPI's contribution to maize yield was 18.6–156.8% higher than that of SCI and SMI. Partial least-squares path modeling identified SPI as a direct influence on SMI and SCI, making it the largest driver indirectly improving SQI and maize yield in Mollisols. Therefore, SIT treatment is a highly effective soil management practice for improving soil quality and crop yields in the Mollisols region. Our study provides guidance for enhancing soil environmental quality and designing sustainable agricultural policies in the Mollisols region and other arable soils.

**Acknowledgments**

The study was supported by the National Key R&D Program of China (2022YFD1500100), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA28070100), the Chinese Agriculture Research System (CARS04), and the Young Scholars Program in Regional Development, Chinese Academy of Sciences (2022-027).

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# Divergent Pathways of Soil Pore Structural Recovery under No-Till across a Semi-Arid to Semi-Humid Climatic Gradient

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**ABSTRACT**

Conservation tillage, specifically no-till (NT), is globally promoted for soil health recovery. However, its impact on soil physical architecture and associated functions is highly site-specific, often modulated by climatic constraints on biological and physical processes. This study investigated the divergent mechanisms driving soil pore structural evolution after five years of NT compared to conventional tillage (CT) across two contrasting climatic zones in Northeast China: a semi-arid region (Beipiao) and a semi-humid region (Shenyang). We employed a multiscale approach combining X-ray computed tomography (CT) scanning for 3D pore morphology, soil water retention curves for pore size distribution, and relative gas diffusivity ($D_p/D_0$) measurements at varying water contents to quantify functional pore connectivity and tortuosity. Results revealed distinct structural responses driven by climatic context. In the semi-humid region, moisture availability facilitated vigorous biological activity under NT, resulting in the development of highly connected, large biopore networks visualized by CT. This translated into significantly higher gas diffusion efficiency at a given air-filled porosity, indicating reduced pore tortuosity compared to CT. Conversely, in the semi-arid region, moisture limitations constrained macropore formation. NT improvement was characterized by enhanced physical stabilization and an increase in meso- and micropores critical for water retention, with gas transport relying on a less tortuous, yet finer, pore network rather than large biological channels. Our findings demonstrate that climate fundamentally dictates the mechanistic pathway of structural recovery under NT—shifting from biologically-driven macropore construction in wetter climates to physical stabilization and micropore reorganization in drier regions. This underscores the need for climate-adaptive criteria when evaluating soil structural optimization in conservation agriculture.

**Keywords:** Soil pore structure; X-ray CT; Gas diffusion; Climatic gradient; No-till;

**Acknowledgments**

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# Coupling effects of freeze-thaw action and thawed soil depth on snowmelt erosion under near-surface hydrologic conditions in the Mollisol region of Northeast China

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**ABSTRACT**

Near-surface hydrologic conditions (NHC), including drainage, saturation, and seepage, are key drivers for summer rainfall-induced erosion. Among these, saturation and seepage intensify erosion compared to drainage, with their effects remaining relatively consistent under controlled hydraulic gradients. However, it remains unclear whether the erosive characteristics of NHCs, influenced by freeze-thaw action (FTA) and thawed soil depth (TSD) differ under winter-spring snowmelt erosion compared to summer rainfall-induced erosion. The Mollisol region of Northeast China is highly susceptible to both erosion types, posing a significant threat to agricultural productivity. This study investigated the impact of FTA on the erosive characteristics of NHCs during snowmelt erosion and compared it with summer rainfall-induced erosion. The mechanisms underlying these differences and the influence of FTAs on varying TSDs were identified. Three NHC conditions (drainage, saturation, and seepage) were tested alongside five TSDs: 1 cm (FS1), 3 cm (FS3), 5 cm (FS5) and 10 cm (FS10), as well as an unfrozen control (10 cm, UFS10). Experiments were conducted on silty clay loam with an 8.75% slope under three meltwater intensities (2, 3 and 4 L/min). Results showed that FTA enhanced the erosive effects of saturation and seepage compared to summer rainfall-induced erosion, by altering pore-water pressure. This effect was most pronounced under FS5 and FS10, where erosion increased with TSD stabilized. The contribution of NHCs to erosion rate reached 51.71% under FS5 and FS10, representing a 902.13% increase compared to UFS10 (5.16%). In contrast, no significant differences in erosion rate across NHCs were observed in FS1 and FS3 ($P > 0.05$). These results demonstrate that the erosive effects of NHCs on frozen slopes are strongly TSD-dependent and provide novel insights into the mechanisms of snowmelt erosion. Consequently, these findings are critical for considering NHC effects in snowmelt-dominated erosion process in cold and hydrologically variable regions.

**Keywords:** Near-surface hydrologic conditions; Freeze-thaw action; Thawed soil depth; Pore-water pressure; Snowmelt erosion; Mollisol region of Northeast China

**Acknowledgments**

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# Intensification tradeoff for crop yield under different tillage scenarios towards agricultural sustainability of Black Soils

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## ABSTRACT

Northeast China serves as a core production region for maize and soybeans, yet it has long faced the dual challenges of black soil degradation and the sustainability of grain production capacity. Conservation tillage is increasingly recognized as a key approach to achieving the dual goals of protecting black soil and ensuring food security. However, its yield effects may exhibit considerable spatial heterogeneity under different climatic, soil, and topographic conditions, leading to inconsistent outcomes for the same practice. As a solution, we employed meta-analysis, four machine learning models, and the Shapley Additive exPlanations (SHAP) method to quantify the impacts of different conservation tillage practices on crop yield in Northeast China, identify their driving factors, and predict the spatial suitability of these practices. The results showed that, compared with conventional tillage, conservation tillage significantly increased crop yield by approximately 9.96% overall. Specifically, no-till/reduced tillage (NT/RT) increased yield by 11.86%, deep plowing (DP) by 10.58%, and straw return (SR) by 10.43%, which were higher than crop rotation (CR). SHAP analysis revealed that temperature, precipitation, and soil organic matter (SOM) were the dominant factors influencing yield, although their relative contributions varied across practices. Model comparisons revealed that Extreme Gradient Boosting (XGBoost) and Categorical Boosting (CatBoost) significantly outperformed Random Forest (RF) and the Light Gradient Boosting Machine (LightGBM). Spatial suitability analysis further delineated the suitable ranges for each practice. For instance, CR showed pronounced yield-increasing effects in the eastern and southern Songnen Plain, the Liaohe Plain, and areas with severe salinization in northwestern Jilin Province. SR was suitable for plains with favorable hydrothermal conditions but had limited effects in low-temperature or arid regions. NT/RT performed well in plains and western sandy areas but exhibited reduced effectiveness in regions with insufficient accumulated temperature. DP significantly increased yield in the core areas of the Songnen Plain but was unsuitable for regions characterized by low temperature, aridity, or steep slopes. Our findings could serve as important References for targeted promotion and implementation of conservation tillage in the region, which is of great significance for ensuring regional food security and the sustainable utilization of black soil resources.

**Key words:** Northeast China; conservation tillage; meta-analysis; machine learning; SHAP analysis; spatial suitability.

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# ESTABLISHMENT OF A NATIONAL DIGITAL DATABASE AND INFORMATION SYSTEM FOR AGRICULTURAL SOILS IN MONGOLIA UNDER THE AFACI PROJECT

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**ABSTRACT**

Mongolia is a vast, land-dominated country in East Asia, where over 85 % of the territory is rangeland and only 0.7 % is arable land. The country is characterized by a harsh continental climate with increasing temperatures, low precipitation, and high spatial variability. Over the past six decades, air temperature has increased by approximately 2.46 °C, leading to intensified land degradation in pasturelands and enhanced soil erosion in cultivated areas.

Agricultural sustainability in Mongolia is strongly dependent on effective soil management; however, systematic soil monitoring and digital soil information systems remain limited. To address this gap, the AFACI-supported project aims to develop a National Soil Information System (NSIS) through the integration of legacy soil data, laboratory analyses, field surveys, and geospatial technologies.

The project focuses on building a harmonized national soil profile database, developing digital soil property maps, and supporting WRB soil classification correlation. Open-source GIS and remote sensing tools were applied for data processing, harmonization, and spatial modelling.

Results show that 9,891 soil observations, 1,550 soil profiles, and more than 6,000 analytical datasets were compiled and harmonized. Ten national soil property maps, including SOC, pH, salinity, nutrients, and texture components, were produced. The developed NSIS integrates soil profile, analytical, spatial, and metadata databases, enabling data storage, visualization, mapping, and decision support. This system provides a scientific foundation for sustainable land management, climate change adaptation, agricultural planning, and participation in the Soil Atlas of Asia initiative.

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# SOIL ORGANIC CARBON CHANGES UNDER LONG-TERM CULTIVATION IN MONGOLIAN KASTANOZEMS

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**ABSTRACT**

Soil organic carbon (SOC) is a key indicator of soil fertility and ecosystem functioning. Long-term cultivation can significantly alter SOC quantity and its distribution among functional fractions, particularly in fragile semi-arid ecosystems. This study evaluated the effects of long-term land use on SOC stocks and carbon fraction distribution in cultivated Kastanozems of Mongolia. The study was conducted in Jargalant soum of Tuv province, where a field cultivated for more than 50 years was compared with adjacent virgin land as a control. Soil samples were collected from the 0–5 cm and 5–10 cm layers. Soil agrochemical properties were analyzed, and SOC fractions were separated into particulate organic matter (POM), coarse fraction (>20 µm), and fine fraction (<20 µm) using density fractionation methods. SOC stocks were estimated using bulk density and carbon concentration data. The results showed a clear decline in soil fertility indicators under long-term cultivation. Soil organic matter content decreased to 1.71% in cultivated soil compared to 3.98% in virgin soil. SOC stock in the 0–5 cm layer was 442.8 g $m^{-2}$ in cultivated soil, while virgin soil contained 782.8 g $m^{-2}$, representing a reduction of 43.5%. Fractionation analysis indicated a decrease in the fine mineral-associated fraction (<20 µm) and particulate organic matter, while the proportion of the coarse fraction (>20 µm) increased under cultivation. These results indicate less stable carbon storage and faster decomposition of soil organic matter. The findings demonstrate that long-term cultivation in Mongolian chestnut soils significantly reduces SOC stocks and alters carbon fraction distribution, leading to soil fertility decline. Sustainable soil management practices, including nutrient replenishment and conservation-oriented tillage systems, are required to maintain soil health under ongoing agricultural use.

**Keywords:** organic matter, land use change, carbon fractions, soil fertility, cropland

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# Sambaquis as Records of Soil Management by Original Populations in the Holocene

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**ABSTRACT**

Black soils are vital for global food security and environmental sustainability due to their exceptional fertility and high organic carbon content. In Brazil, they occur in particular environments and occupy small areas with notable variation of climate, relief and parent material. Among them, a group of Black Soils originated from anthropic influence which modified significantly the soil properties. The most well-know is the Amazonian Dark Earths (ADE), and secondary the *sambaquis* or shellmounds. The *sambaquis* are situated along the Brazilian coast, and were constructed by fisher-hunter-gatherer groups through the long-term accumulation of shells, fish bones and sediments, combined in a complex stratigraphy, with material that includes burials, lithic and bone artifacts, charcoal, and food waste. Both types are included in the definition of Black Soils (FAO, 2022) and they have an important function of cultural heritage. Studies of these soils elucidate not only archaeological issues, but also soil management regarding practices that resulted in their high fertility, markedly high organic carbon (Corg), phosphorus (P), calcium (Ca) and other nutrients. An example is the increasing agricultural usage of biochar; practice originated from the studies of ADE. For this study, two locations of *sambaquis* in the coast of Brazil were selected: i) São José de Ribamar, Maranhão State, northeastern region; and ii) Cabo Frio, Rio de Janeiro State, southeastern region. Morphological, chemical and physical attributes of the soils in the *sambaquis* were evaluated and the results will be presented. Other analysis was: sequential phosphorus fractionation, quantification of shell contents, and magnetic susceptibility (MS) and spectroradiometry in the *sambaqui* from Rio de Janeiro, where a correlation was observed between MS, P bioavailability, Ca and Corg content in the soil. These characteristics are essential for understanding the dynamics of specific pedogenic processes in *sambaqui* soils. Overall, it is recommended urgent public policies and environmental education actions to preserve these archaeological sites, since their study may provide with insights of practices to sustainable management and restoration of Black Soils in other environments.

**Keywords:** Anthropic soils, indigenous knowledge, tropical black soils.

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# Degradation severity shifts environmental controls and vegetation effects on soil respiration in restored Mollisols

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## ABSTRACT

Soil respiration (Rs) is a critical component of the terrestrial carbon cycle, yet how degradation severity and vegetation restoration jointly regulate Rs dynamics in degraded ecosystems remains poorly understood. We conducted a field experiment in Northeast China's degraded agricultural soils, establishing a factorial design with three degradation levels (lightly degraded, LD; moderately degraded, MD; severely degraded, SD) and five plant treatments (*Populus simonii* × *P. nigra*, P. xh; *Larix gmelinii*, Lg; *Amorpha fruticosa* L., Af; *Bromus inermis* Leyss., Bi; and bare soil control, CK). Rs was measured biweekly during the growing seasons alongside soil physicochemical properties, microbial biomass, enzyme activities, and plant growth metrics. Results showed that daily mean Rs in CK declined significantly with increasing degradation severity (LD: 3.50, MD: 0.80, SD: 0.51 μmol $CO_2$ $m^{-2}$ $s^{-1}$)), driven by reductions in soil organic carbon (SOC) and total nitrogen. Vegetation restoration significantly enhanced Rs across all degradation levels, with effects most pronounced in SD where the ranking was Bi (107% increase) > Af (85%) > P. xh (76%) > Lg (59%) relative to CK. Structural equation modeling revealed that degradation primarily reduced Rs through direct SOC depletion and indirect pathways via decreased nutrient availability and enzyme activities. Importantly, the dominant environmental driver of Rs shifted from soil temperature in LD (β = 0.373) to soil moisture in SD (β = 0.412), reflecting degradation-induced alterations in enzyme activity and moisture constraints on heterotrophic activity. Vegetation effects operated through a cascade mechanism: SOC accumulation enhanced nutrient availability, which increased enzyme activities and subsequently stimulated Rs. Our findings demonstrate that degradation severity fundamentally reshapes Rs regulatory mechanisms, and that selecting plant functional groups matched to degradation conditions can effectively restore soil carbon dynamics in degraded ecosystems.

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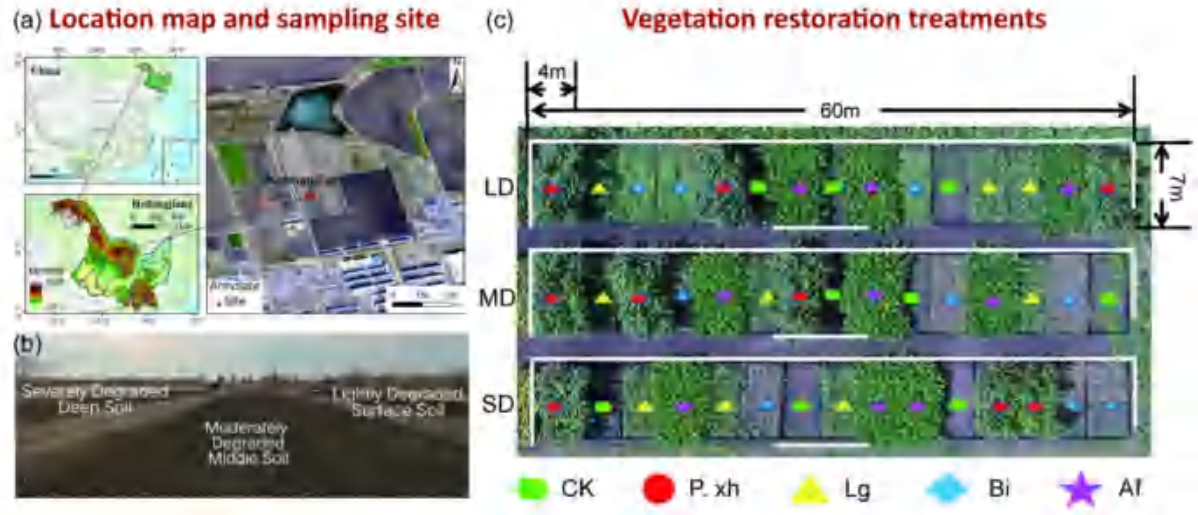



Figure 1. Location and overview of sampling plots and major vegetation types.

# Comparative Study on Conservation and Utilization of Black Soils in China and Argentina

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**ABSTRACT**

Effective conservation and utilization of black soil resources is an inevitable requirement for ensuring global food security and realizing sustainable agricultural development. This study systematically examines the core challenges and the degradation status of black soils in two representative black soil regions of China and Argentina. A comparative analysis is conducted on the key degradation indicators, including black soil layer thickness, soil erosion, soil fertility quality, soil acidification, and soil geochemistry elements accumulation. In addition, the study also compares the application of agricultural chemicals (fertilizers and pesticides) and the level of agricultural mechanization in China and Argentina. Both China and Argentina have adopted conservation tillage practices in the protection and utilization of black soils, actively engaged in agricultural science and technology innovation and have achieved notable progress. China focuses on the integration and application of a variety of conservation tillage techniques, such as less-till, no-till and straw mulching, and has introduced a series of laws and regulations on black soil conservation. While Argentina combines no-tillage with straw mulching and diversified crop rotations to promote the implementation sustainable practices. The two countries have their own characteristics, which provide multiple References examples for global black soil conservation and sustainable utilization. In the future, it is necessary to strengthen international exchanges and cooperation in the conservation and utilization of black soil between the two countries and even the world, strengthen the construction of technology research and development and application system, increase scientific and technological innovation and policy support, realize the complementary advantages of black soil conservation in different countries and regions, and promote and realize the conservation and sustainable utilization of global black soil resources.

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# DSS for Sustainable Management and Conservation of Black Soils in Russia

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**ABSTRACT**

The general trend of increasing average monthly temperatures during the warm period, characteristic of global climate change, determines a gradual increase in the sum of active temperatures during the growing season of crops, creating potentially more favorable conditions for the development of highly profitable commercial crop production on Black soils in Russia. At the same time, the frequent frequency and increased intensity of adverse weather conditions lead to a marked increase in the environmental and economic risks of intensive agricultural production in the most regions with Blak soils. The 21st century is characterized by frequently changing market requirements, regular updating of zoned varieties, fertilizers and plant protection products that are differentially effective depending on weather conditions and soils, potential yields and payback of crops. A steady increase in the cost-effective production of high-quality and affordable food products in demand on the market requires the use of the best agricultural technologies in specific soil and agroecological conditions, affordable for ordinary land users.

Mesorelief is usually the dominant unregulated limiting agroecological factor in agrolandscape with Black soils (Fig. 1). Slope mesorelief determines the intensity of erosion processes, the thickness of humus horizons, the depth of carbonates, and reserves of soil productive moisture, on which wheat yield largely depend.

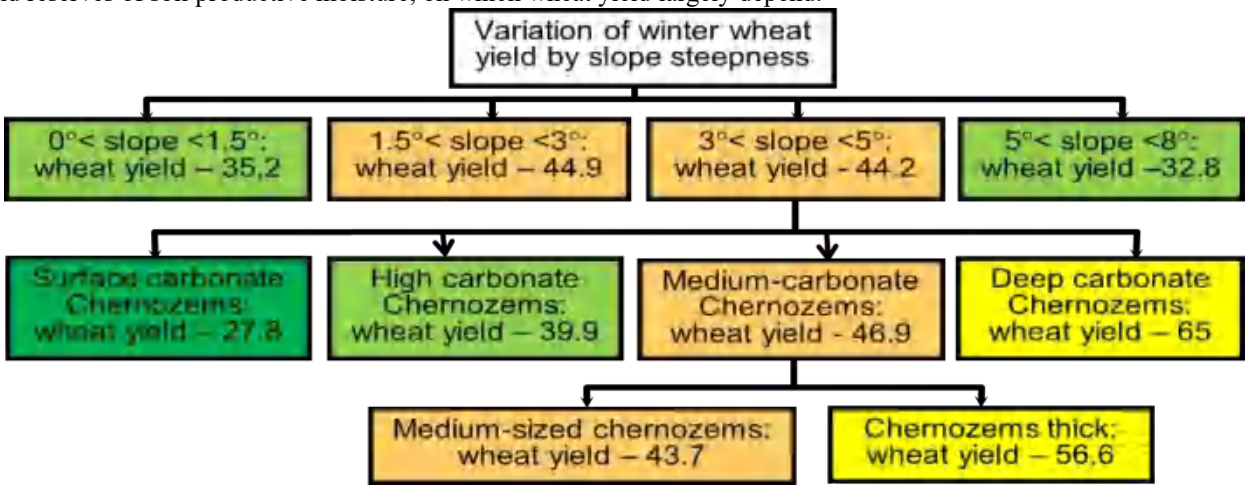



Fig. 1. Regression tree of the agroecological factors influence on the winter wheat yield (dt/ha) within representative field on Black soils in Kursk region.

In the context of global climate change with the shift of the second summer maximum precipitation by 2-3 weeks in the arid areas of Volga region and the Southern Urals, an effective means of minimizing agroecological risks of reducing durum wheat yields became to shift its sowing time by 1.5-4 weeks. The effect of this turned out (plus 10-35% of crop yield) to be higher than the aftereffect of the use of micro fertilizers – both in 2022 with the average annual rainfall of the growing season, and in the dry year 2023, at the same level of technological costs.

Over the past 10 years, the area of Black soils processed in Russia using No-till technology has increased by more than 3 times and exceeded 5 million hectares in 2023 (according to a review of data from the National Partnership for Conservation Farming). According to the results of 10-year monitoring of No-till technology, the effect of organic carbon accumulation in the topsoil has been confirmed with an average reduction in annual $CO_2$ emissions by about 1 ton per hectare.

Intelligent DSS for agroecological optimization of agriculture are necessary for the rapid adaptation of farming systems and flexible elements of the best available agricultural technologies to rapid changes and a wide variety of regional climate, soils and technologies that are specific for different regions with Black soils in Russia.

# Status of Black Soils in Rio de Janeiro: a legacy of mismanagement and recommended practices to reclaim their potential

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**ABSTRACT**

Black Soils are recognized for their role in global food security and environmental sustainability. This is on account of their natural fertility and high-activity clays content that are essential in storing organic carbon (Corg) through the formation of highly stable organo-mineral complexes, and the high content of nutrients supporting agricultural production. Black Soils are less extensive in Brazil and their formation is highly dependent on parent rocks and unique environmental conditions to provide their mineral properties and organic matter accumulation. In the Brazilian Southern region of Rio de Janeiro, these soils are scarce and often associated with localized occurrences of diabase and basalt rocks, and calcareous materials. For this study, 12 profiles were selected following the definition of Black Soils (FAO, 2022), located in Rio de Janeiro state under different soil forming factors. Two profiles were initially classified in the 1st category of Black Soils and the other 10 in the 2nd category. Seven profiles were under degraded pasture, and five under no agricultural usage. Morphological, chemical and physical properties were evaluated, with the purpose of analyzing degree of degradation of these soils based on their properties and current land usage. Along history, the state of Rio de Janeiro has experienced profound exploitation of its rural landscapes, where land-use comprised intensive and successive cycles with sugarcane and coffee after removal of the Atlantic Forest. Today, approximately 70% of Rio de Janeiro's agricultural area is covered by pastures, with more than half showing some degree of degradation. The lack of conservation and unsustainable land management, as well as the history of intensive agricultural expansion, have led to widespread soil degradation, causing the few existing Black Soils to be impacted negatively by accelerated erosion and nutrient depletion, greatly diminishing their agricultural potential and threatening the environmental services. The studied profiles currently under no usage had the highest Corg contents, high base saturation and cation exchange capacity, indicating some recovery or preservation of characteristics of Black Soils of category 1. For the other soils, there were major changes in the properties due to accelerated degradation, primarily when the relief is more undulated. A significant portion of the profiles require implementation of sustainable soil management practices to safeguard their environmental services and to reinforce their land capability.

**Keywords:** Tropical Black Soils, Agricultural Usage, Atlantic Forest.

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# Effects of Full Maize Straw returning on Soil Physical Properties and Maize Yield

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**ABSTRACT**

Straw returning to the soil plays a significant role in enhancing soil fertility. A field experiment was conducted to optimize the combination of maize straw returning and tillage method, in order to support the sustainable and efficient maize production in Fuxin, Liaoning Province, China. With conventional shallow roary tillage after no-straw returning without or with biodegradable mulches (RTNN, RTNB) and no-tillage after straw-covering (NTS) as controls, six treatments were established, including plow tillage 30cm-depth after straw returning without or with biodegradable mulches (PTSN, PTSB), deep rotary tillage 30cm-depth after straw returning without or with biodegradable mulches (RTSN, RTSB) and deep rotary tillage 30cm-depth after organic fertilizer application without or with biodegradable mulches (RTON, RTOB). Maize yield and soil physical properties such as bulk density, field capacity (FC), soil total porosity percentage, aeration porosity, capacity porosity and so on, were explored. The results showed that compared to the controls, PTSN significantly increased FC. PTSB also significantly improved FC compared to NTS and RTNB. There were no significant differences in field capacity among RTON, RTSN and PTSN, with no influence from mulching or not.

Compared to NTS, all other treatments reduced soil bulk density and increased both total porosity and capillary porosity. Furthermore, compared to NTS, all the treatments of straw returning and organic fertilizer application (PTSN, PTSB, RTSN, RTSB, RTON and RTOB) significantly increased maize yield. In conclusion, straw returning or organic fertilizer application can effectively enhance cultivated land fertility and improves soil physical properyies. These findings provide a theoretical foundation and data support for the rational utilization of maize straw and soil carbon sequestration.

**Keywords:** full maize straw returning, soil physical properties, maize yield, field capacity

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# Assessment of the health of tropical black soils in the context of intensive agriculture: the case of the Vertisols of Tcheboa , Northern Cameroon

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**ABSTRACT**

Black soils, although rare globally, are essential for food security and climate change mitigation. In Tcheboa , their intensive exploitation to meet food needs threatens their health. This study analyzes the effect of agricultural intensification on the health of these soils. Five land cover types were identified, and samples were taken at three depths (0–10 cm, 10–20 cm, 20–30 cm) and then analyzed in the laboratory. The results reveal high variability among crops. Sorghum fields and fallow land have the highest surface organic carbon content (2.73% and 2.20%, respectively) and the largest carbon stocks (21.92 t/ha and 19.22 t/ha, respectively). In contrast, soils under onions and onion seeds show lower content (1.98% and 1.54%, respectively). The C/N ratio is higher under sorghum and fallow land. Phosphorus increases with depth under sorghum and onions (up to 3.73 ppm), while it remains low under peanuts and fallow. Soil bioavailability (SBA) reaches 14.56 meq / 100 g at 10–20 cm under fallow, where the highest potassium content is also observed (3.56 meq / 100 g). Nitrogen decreases with depth (0.17% to 0.10%). The overall soil health index, weighted by parameters, ranks onions (0.59) and fallow (0.58) at the top, followed by sorghum (0.54). Onion (0.45) and peanut (0.31) seeds are the most degraded. To restore the health of these soils, organic fertilization, cattle grazing followed by chemical fertilization, and fallow periods can be implemented. These results will enable policymakers and farmers to implement sustainable management of these soils.

**Keywords** : Black Soils; Soil health; Intensive agriculture; North Cameroon

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# Assessing the nutrient potential and carbon stock of black soils in the Goma area (Eastern DRC)

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**ABSTRACT**

Black soils are known as the breadbasket of global food production and a key element in combating climate change due to their high fertility and organic carbon content. However, they are subject to degradation due to climate change and overexploitation. This study aims to investigate the nutrient and carbon stock potential of black soils in an area within the city of Goma (Eastern DRC) to promote their effective management. To this end, three pits were dug along a toposequence, and a total of twenty-seven (27) samples were collected from different horizons for physicochemical analysis. This equates to nine samples per profile, representing three horizons for each profile. The results showed that the available phosphorus content was very high at the top of the slope (70.89 mg/kg) and low at the bottom (59.42 mg/kg). Furthermore, the surface horizons exhibited higher phosphorus levels compared to the underlying horizons. For nitrogen, the mid-slope profile showed the highest content in the surface horizon compared to the others (0.35%). Exchangeable bases $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$ showed moderately low to medium values in all profile horizons. Soil organic carbon (SOC) was highest in the mid-slope profile at 6.7%, followed by the bottom-slope profile (5.53%). All SOC levels were high, with the lowest value being 3.84%. Carbon stock reached up to 345.4 t/ha in the deeper horizons, indicating the role of these soils in mitigating climate change. The results of this study demonstrated the importance of these soils both for fertility, ensuring food security, and for combating climate change. These results will allow for the sustainable management of these soils, which are highly vulnerable to degradation.

**Key words: Black Soil- Nutrient Potential- Carbon Stock- Democratic Republic of Congo**

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# Evaluating the Effectiveness of Conservation Tillage in the Black Soil Region of Northeast China Based on the Apparent Characteristics of Crop-Residue-Soil

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**ABSTRACT**

The black soil region of Northeast China is crucial for national food security(Xiao et al., 2024) but suffers severe degradation from intensive use(Wang et al., 2023). While conservation tillage is essential, accurately evaluating its effectiveness remains challenging due to limitations of current monitoring methods: Fixed-site observations offer high-precision data but lack generalizability—for instance, "no-till with straw return" may increase soil organic carbon while reducing maize yield in some areas(Chen et al., 2023) but show negligible effects in others(Jiang et al., 2025); Remote sensing enables rapid large-scale monitoring but is constrained in detecting internal soil properties by factors like moisture and vegetation cover(van Wesemael et al., 2023); Process models support long-term prediction yet are highly dependent on parameterization(Asseng et al., 2013); Soil surveys provide authoritative data but involve high costs and multi-year efforts, as seen in the 2025 national black soil survey.

To address these gaps, this study developed a field-applicable "Look-Fold-Dig-Pinch-Measure" methodology for rapid assessment of crops, straw, and soil. A simplified field manual converts technical indicators into graded scores, enabling farmer-led monitoring. Ground data collected through this system support remote sensing validation and model calibration while revealing underlying mechanisms.

Field surveys across four provinces demonstrate that straw return-especially soybean straw-enhances soil structure and erosion resistance, whereas corn straw return favors crop growth. These findings support region-specific tillage optimization. Future work will integrate apparent indicators with multi-source remote sensing via quantitative models, establishing a "point-to-area" monitoring framework to advance apparent indicators from qualitative observation to quantitative diagnosis, supporting the development of a apparent feature-based health evaluation system for black land conservation.

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# Depth-dependent responses of soil microbial communities to subsoil tillage with straw enhance soil quality and crop yield

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**ABSTRACT**

The improvement of soil quality through microbial regulation is crucial for soil fertility and crop yield. However, the mechanisms underlying the enhancement of deep soil quality under conservation tillage remain poorly understood. Based on a 6-year field experiment in the Mollisol region of Northeast China, comparing conventional no-tillage without straw (NT) to two conservation treatments: no-till with straw mulching (NTS) and subsoil tillage with straw mulching (STS). Soil bacterial and fungal community were analyzed to 1 m depth, alongside soil properties and a soil quality index (SQI) linked to maize yield. Both NTS and STS significantly enhanced microbial richness and diversity relative to NT, but displayed distinct depth-dependent patterns. NTS mainly increased bacterial diversity in the 0–10 cm layer by adding organic matter, whereas STS had the strongest effects in deeper layers, boosting fungal diversity in the subsoil (20–60 cm). Both practices promoted more complex microbial co-occurrence networks compared with NT, with STS exhibiting the highest network complexity, including more nodes, edges, and keystone taxa—particularly in subsoil. NTS mainly stimulated surface bacterial communities, whereas STS facilitated downward nutrient movement and supported diverse fungi and keystone taxa at depth. These shifts were functionally meaningful: NTS and STS improved SQI by 9–17% compared with NT, and STS yielded the highest gains in SQI and crop yield. The depth-stratified microbial responses, a bacteria-driven nutrient cycling in topsoil vs. a fungus-mediated carbon and nutrient pathway in subsoil, link closely to soil nutrient availability under STS. Our findings highlight that integrating straw mulch with subsoil loosening synergistically leverages bacterial and fungal communities across soil profiles, thereby enhancing soil quality and crop yield. This depth- dependent management offers a promising route to improve agroecosystem sustainability by tapping the potential of subsoil microbial communities.

**Keywords:** Straw mulching; Subsoil tillage; Soil depth; Soil Quality; Soil microbial community; Co-occurrence network.

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# Sustainable Management and Restoration of Chernozem (Black Soil) in Vojvodina, the Republic of Serbia

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**ABSTRACT**

Chernozem or black soil, the most fertile soil type, covers approximately 1,000.000 ha of agricultural soil in Serbian part of the Pannonian Plain, and over 3,500,000 hectares across the entire multi-country plain. Studies in the Southeastern European region have shown alterations in chemical properties of soil, primarily characterized by significant soil organic carbon (SOC) depletion, and generally this trend was also confirmed in Serbia. The biggest threats to Chernozem soil health in Serbia include: intensive agriculture, erosion, organic matter decline, salinization and land use change. The Vojvodina province has been identified as the most vulnerable region in Serbia to wind (aeolian) erosion, due to flat topography, the lowest levels of forest cover in Europe (approximately 6.37%), and intensive agricultural practices. It is estimated that wind erosion risk is high, and even 60.41% of soils of Vojvodina is classified in the hazardous sensitivity category. In our study, the highest historical loss of SOC stock due to the conversion of native ecosystems (forest and meadows) to arable land was obtained in Chernozems (16-18%) compared to other soil types, due to intensive agricultural production and tillage. However, field experiments demonstrated that specific soil conservation measures can help to maintain SOC. Long-term trials reveal that integrating manure or harvest residues (HRs) significantly boosted crop yields. While mineral fertilizers showed no positive effect on SOC, treatments incorporating HRs, manure, or liquid manure increased both SOC concentration and stock compared to control groups or those receiving only mineral fertilizers. Compared to plowing, no-till and disc-tillage treatments have more SOC. Organic farming has been increasingly recognized as a sustainable alternative to conventional agriculture, largely due to its potential to preserve soil health and reduce environmental degradation. Long-term organic management (>10 years) in Chernozem compared to conventional systems, reduced SOC losses by 10.9% and improve physical soil properties. In conclusion, agricultural practice lead to decrease of SOC in all investigated field trials, because arable soils are source of SOC rather then sinks. To enhance SOC pool it is necessary to limit tillage and to incorporate of biomass with HRs and organic fertilizers. Recycling and use of plant- and animal-derived organic residues (e.g. compost, biogas residues) is and important element of sustainable management of organic waste, which has a great potential in Serbia due to limited use in agriculture so far. In general, the conservation and restoration strategies should include minimizing soil disturbance, maximizing soil cover as well as biodiversity. Moreover, introducing systematic monitoring and creating a centralized database at the national level is necessary for setting the goals in the field of preserving the soils in Serbia.

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# Soil-landscape Modeling on Experimental Plots: RECSOIL on Black Soils in Central Russia

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**ABSTRACT**

Black soils are well known as the world's food basket, but suffer from nutrient imbalances, acidification, compaction and soil biodiversity loss (INBS GSP FAO). The RECSOIL initiative was launched by the GSP FAO to expand soil management coverage with a focus on the binding of soil organic matter (SOM) to improve soil health. SOM serves as a key example of land productivity and serves as an indicator of land degradation in RECSOIL research. The RECSOIL in Russia was launched in 2024 on a 200-hectare pilot plot on black soils (Luvic Chernozems).

Given the specific nature of farms focused on the production of commercial crops, the presence of fallow land in crop rotation, and the lack of opportunities to use domestically produced manure, measures have been taken to ensure carbon sequestration and deposition in arable soils or to reduce its losses, starting in 2025.

We collected the legacy soil data and fresh soil samples from the 0-30 cm layer. Two sample strategies were used: standard agronomic methods - divided into polygons according to GOST R 58595, and a randomly stratified scheme for subsequent geostatistical analyze. Soil analysis were carried out at the local RUSOLAN laboratory, part of the global network of soil laboratories (GLOSOLAN), to respond to the need for harmonizing soil analytical data and support evidence-based decision making for sustainable soil management.

Ground-based field monitoring is conducted throughout the season, and the farm is sequentially introducing green manure (GM) into the grain crop rotation as a catch and fallow crop. The farm is also transitioning to an organo-mineral plant nutrition system, supplementing the existing mineral nutrition system with small-scale organic granular fertilizers (FYM). For the fields under study, a crop rotation in 2025-2029 was assumed: fallow to sorghum (GM), winter wheat +GM+FYM, soybeans, winter wheat +FYM. Forecast of stock dynamics was made using the RothC model until 2030, Mg C ha-1.

Calculation of C input based on the adopted crop rotation and the planned crop yields according to the technological maps shows that the existing crop rotation is insufficient to maintain long-term C reserves in each field at the lower productivity quartile level; it is necessary to provide an additional average long-term annual input of 0.2-0.7 Mg C ha-1. To achieve median values, it is necessary to provide an additional average long-term input of 0.5-0.9 Mg C ha-1, and the upper quartile – 1-1.5 Mg C ha-1. This can be achieved both through the proposed changes in crop rotation and through the application of organic fertilizers. Accordingly, an increase in soil C reserves can be expected with C input exceeding these values.

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# Assessment of water resources carrying capacity and identification of obstacle factors in the Songnen Plain based on a combined weighting-matter-element extension model

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**ABSTRACT**

Understanding water resource carrying capacity (WRCC) is necessary to identify informed water resource conservation measures for regional development and sustainable growth. The WRCC system comprises socio-economic, natural ecological, and water resource subsystems. We propose a framework that integrates a WRCC indicator system, combined weighting-based matter-element extension model, and an obstacle degree model for the dynamic evaluation of WRCC. For Songnen Plain, China, we report that the WRCC in most areas was overloaded or transitioning toward overload from 2012 to 2017, but that conditions optimized from 2018 to 2021, except in the Heihe area. Optimal WRCC conditions occurred in the central Songnen Plain region, but poorer conditions occurred in northern and southern regions. From 2013–2021, the natural ecological subsystem carrying capacity exceeded that of water resource and socio-economic subsystems, and performed best in the Changchun area; the Tsisihar area socio-economic subsystem had the highest carrying capacity and was balanced from 2018–2021. The coupling coordination degree among urban subsystems reached a high level or above in all cases, accounting for 94.44%. From 2012–2021, the obstacle degree of the socio-economic subsystem plummeted from 97.8% in 2012 to 40.57% in 2018, only to rebound sharply to 94.91% by 2021, those of the water resource subsystem from 57.54% to 56.70%, and those of the natural resources subsystem, from 66.8% to 46.23%. WRCC was primarily influenced by socio-economic and water resource subsystems. Dominant obstacle factors shifted from agriculture to socio-economic structure, with key limiting indicators including water yield modulus, water consumption per 10,000 yuan of GDP, Spatially, the obstacle factors exhibited differentiated spatial association patterns. efficiency of water resource development and utilization, and wastewater discharge. These results and insights provide a framework to facilitate integrated assessments of WRCC at various spatial scales.

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# Unveiling soil organic carbon sequestration potential and driving factors of global black soil: A meta-analysis

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## ABSTRACT

Global black soils are critical to the terrestrial carbon cycle and essential for quantifying global carbon sink capacity. However, SOC sequestration assessments often rely on short-term data and linear assumptions, failing to reflect long-term accumulation trends under organic fertilization. To address this, we conducted a meta-analysis integrating long-term (>20 years) data from 9 black soil sites across 4 global regions to evaluate the impacts of fertilization on SOC sequestration potential. Three treatments were examined: no fertilizer (CK), chemical fertilizer (CF), and combined organic and chemical fertilization (O+CF). Our results showed that SOC exhibited a net depletion under the CK treatment, while the O+CF treatment significantly increased SOC sequestration. Under the O+CF treatment, long-term additional C input drove SOC sequestration to exhibit a non-linear temporal change eventual saturation, with levels of 39.44 (US), 108.81 (Canada), 49.64 (Russia), and 82.42 (China) Mg $ha^{-1}$. Saturation times differed by site: ~80 years (US), ~30 years (Russia), 45 years (Canada), and 50 years (China), all stabilizing at an annual growth rate <0.001%. Management practices (duration and C input) were key drivers, with saturation triggered at a cumulative C input of 83.63 Mg C $ha^{-1}$ across the global black soils region. At saturation, global black soils' potential SOC sequestration was ~1.31 (US), 0.97 (Canada), 13.12 (Russia), and 38.77 (China) Pg C, with global application of organic fertilization to these soils capable of offsetting ~0.05% of annual global soil C emissions (~90 Pg C). This study highlights the unique value of long-term field datasets. Accurately quantifying SOC sequestration potential and its environmental drivers in global black soils is vital for climate change mitigation and sustainable agriculture.

**Keywords:** Carbon sequestration; Soil carbon saturation; Global black soil; Organic addition

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# Uncovering the Biophysical Mitigation Potential of Off-Season Croplands across Global Black Soil Regions

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## ABSTRACT

Off-season croplands, defined as the period between harvest and subsequent sowing, play an underrecognized role in land–atmosphere interactions. In major black soil (Mollisol) regions, research has primarily focused on crop productivity and carbon dynamics, leaving the biogeophysical implications of post-harvest field conditions largely unexplored. Crop residue cover, a core practice of conservation agriculture, is well known for its soil and agronomic benefits, yet its large-scale biogeophysical climate effects remain largely unquantified and absent from climate assessments. Here, we present a spatiotemporally continuous, satellite-derived dataset of post-harvest residue cover across the world's four major Mollisol regions from 2000 onward. Leveraging this dataset, we quantify the biogeophysical role of off-season croplands in modulating land surface energy balance, with a focus on shortwave radiative forcing driven by albedo enhancement. Our results show that residue-covered off-season croplands consistently reduce net shortwave radiation across Mollisol regions, generating a measurable and spatially coherent cooling effect. When aggregated across space and time, this biogeophysical signal translates into non-negligible radiative forcing offsets, which we further express in $CO_2$-equivalent units to facilitate comparison with other climate mitigation strategies. This study provides the first global-scale assessment of the biogeophysical climate mitigation potential of residue-covered off-season croplands in Mollisol regions. By explicitly linking conservation-oriented land management to land surface radiative processes beyond the growing season, our findings highlight the importance of incorporating off-season surface dynamics into Earth system models and underscore the role of agricultural management as a nature-based climate solution extending beyond crop production periods.

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# The impact of conservation agriculture on functional microorganism-driven organic nitrogen mineralization and plant–microbe interactions in black soil regions

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## ABSTRACT

The organic nitrogen synthesis and mineralization processes mediated by functional microorganisms are central to achieving efficient nitrogen use in sustainable agriculture. In intensive agricultural systems, long-term and excessive application of mineral nitrogen fertilizers not only intensifies nitrogen losses but also leads to the degradation of functional microbial communities and their metabolic activities, reduces soil organic nitrogen storage and supply capacity, and diminishes plant–microbe interactions—collectively impairing both agroecosystem health and economic sustainability. Conservation agriculture is widely recognized as one of the most effective strategies for promoting sustainable land use, currently implemented on over 9% of global croplands. By integrating straw retention and reduced tillage, this approach modulates functional microbial composition and activity, enhances the synthesis and mineralization of soil organic nitrogen, improves nitrogen fertilizer use efficiency, and strengthens plant–microbe synergies to support stable and high crop yields. However, due to the inherent complexity of soil systems and the unculturability of most microorganisms, the shifts in core functional microbial communities driving organic nitrogen cycling under conservation agriculture remain poorly characterized, and the nature of plant–microbe interactions in this context is still largely unknown.

This study aims to elucidate how conservation agriculture influences functional microorganism-driven organic nitrogen mineralization and plant–microbe interactions through a controlled soil incubation with isotopic labeling followed by a pot experiment. We employed two tillage practices—conventional tillage (CK): complete removal of straw without return, followed by rotary tillage at 30–40 cm depth before spring sowing and direct seeding using a no-till planter; and strip tillage (RT): retention of maize straw on the surface after autumn harvest, with strip clearing and shallow tillage (10–20 cm) prior to spring sowing using a row-cleaning implement, followed by direct seeding. These treatments were applied across two soil layers—surface (0–20 cm) and subsurface (20–40 cm)—and four nitrogen fertilizer rates: zero nitrogen (0N), low nitrogen (60 kg N/ha, 60N), medium nitrogen (120 kg N/ha, 120N), and high nitrogen (240 kg N/ha, 240N). Soils were collected in October 2023 from a long-term conservation agriculture demonstration site established in 2017 in Gaojia Village, Lishu County, Jilin Province, representing both tillage systems at the two depths. After sieving through a 4-mm mesh for homogenization, soils were pre-incubated for 90 days at constant temperature with 15N-labeled $NH_4Cl$ and glucose to enrich microbial biomass-derived organic nitrogen. Following incubation, soils were leached with $CaCl_2$ solution and distilled water to remove residual inorganic nitrogen and substrates, then used in a maize growth pot experiment. Using Raman-activated cell sorting, nanoscale secondary ion mass spectrometry (NanoSIMS), microbial metagenomics and metatranscriptomics, and root metabolomics, we assessed the effects of conservation agriculture on organic nitrogen mineralization efficiency and mineral nitrogen utilization, characterized the active microbial communities involved in organic nitrogen cycling, and deciphered plant–microbe interaction responses.

Results from 15N isotope tracing revealed that, compared to CK, strip tillage increased organic nitrogen mineralization in surface soils by fourfold. Consequently, maize plants exhibited significantly higher uptake of mineralized organic nitrogen and greater biomass accumulation. Total plant nitrogen uptake increased with rising inorganic nitrogen inputs, yet the proportion derived from mineralized organic nitrogen peaked at 60N and declined thereafter. Microbial community and network analyses showed that, relative to CK, strip tillage significantly reduced bacterial abundance in both 0–20 cm and 20–40 cm layers while increasing fungal abundance and enhancing bacterial–fungal interactions. Integration of mineralization data with microbial profiles highlighted the critical role of fungi in driving organic nitrogen turnover under conservation agriculture. NanoSIMS analysis confirmed that active microorganisms in strip-tilled soils responded more sensitively to exogenous mineral nitrogen. Moreover, the turnover rate of microbial-derived organic nitrogen was significantly accelerated under RT. Under nitrogen-deficient conditions (0N, 60N), both treatments induced strong immobilization of microbial-derived organic nitrogen due to nitrogen limitation. However, under sufficient nitrogen supply (120N, 240N), active microorganisms in strip-tilled soils preferentially assimilated exogenous inorganic nitrogen, leading to net mineralization of microbial-derived organic nitrogen. Single-cell Raman sorting coupled with metagenomic sequencing identified key active taxa involved in organic nitrogen cycling in black soils, including members of Firmicutes, Proteobacteria, Bacteroidetes, and Actinobacteria. Notably, the extent of organic nitrogen mineralization was negatively correlated with the relative abundance of these taxa, which were significantly enriched under strip tillage. Root metabolomic analysis further demonstrated that strip tillage markedly enhanced root exudation, particularly of shikimate and phenylpropanoid derivatives, terpenoids, alkaloids, and fatty acids. These compounds showed significant correlations with active functional microbial taxa and exhibited stronger plant–microbe interaction networks under RT. Collectively, these findings identify the key functional microbial groups governing organic nitrogen cycling in black soils and underscore that conservation agriculture enhances plant–microbe functional coordination, thereby improving the turnover and mineralization efficiency of soil organic nitrogen. This study provides mechanistic insights into plant–microbe nitrogen cycling under conservation agriculture, with practical implications for sustainable nutrient management.

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# Transferring Global Pedogenon Insights for Soil Security in Australia

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**ABSTRACT**

Soil is an inherently complex and diverse system. Assessing the capacity and condition, the biophysical dimensions of soil security, requires a robust framework to evaluate soil change over time. Pedogenon concept provides such a framework by defining soil classes based on homogeneity in soil-forming factors at a specific References time, rather than similarity in current soil properties.

This study compares two major applications of the pedogenon concept: a national-scale map for Australia and a recently developed global pedogenon map, both at 90m resolution but derived from different input datasets. The Australian pedogenon map was derived using a total of 27 environmental covariates which were representative of the scorpan factors with varying original resolution of 80 – 270m, and clustered via k-means algorithms. In contrast, the global pedogenon map integrates 22 environmental covariates with a coarser resolution ranging from 90 – 55,000m resolution. These covariates are then subjected to dimension reductions using principal component analysis (PCA) and non-metric-multidimensional-scaling (NMDS) for continuous and categorical variables respectively prior to clustering with k-means algorithm.

The comparison will evaluate the degree of similarity between the two maps and examine how differences in input data and processing methods influence soil security assessments within Australia. A key objective is to develop a method for remapping locally produced pedogenon classes, such as those from the Australian map, onto the legend of the global pedogenon map. This will support scalable and harmonised soil assessments across national and global contexts, improve comparability, and enable integration of pedogenon-based evaluations for soil capacity and condition.

**Keywords:** soil security, pedogenon, assessment framework, capacity, condition

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# Implementing the Soil Security Framework to Assess National Soil Governance: The Case of France

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**ABSTRACT**

The soil security framework apprehends soil sustainability across five dimensions: capacity, condition, capital, connectivity, and codification (Evangelista et al., 2024). France provides a revealing case study of how national governance systems can advance several dimensions of the soil security framework, while remaining weak in others. In the last two decades, France has made significant progress in assessing two of the five soil security dimensions: soil condition and capacity. National monitoring programs and technical frameworks allow measurement of soil quality, ecosystem functions, and potential productivity, providing a strong foundation for evidence-based decision-making. Recognition of soils as a form of natural capital is emerging but remains limited. Mechanisms to account for soil degradation, preserve soil stocks, or incentivize restoration are non-existent or insufficient. Gaps are even more pronounced in the codification and connectivity dimensions. French law does not provide a unified definition or legal status for soil, leading to fragmented and partial protection across urban, agricultural, and environmental regulations. Case law and judicial expertise show inconsistent reasoning, limited transparency, and restricted public access (Baysse-Lainé et al., 2025). The French case study highlights a global need for coherent legal definitions and norms for soil protection. Without shared concepts, translating knowledge of soil capacity, condition and capital into operational laws and policies remain inconsistent. An international convention on soil security could help align national frameworks, like France's, with a common normative structure, needed to support more effective and consistent soil governance.

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# A soil security perspective: Reframing soil indicators for effective governance

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**ABSTRACT**

When assessing soil, biophysical properties often dominate discussions of indicators, informing us about immediate physical aspects. However, most soil health indicators are broad and general, failing to differentiate between multiple soil functions that would more accurately represent the true condition of soil. Consequently, soil health discussions are frequently framed within agricultural contexts, emphasising productivity and human needs while overlooking soil's intrinsic ecological roles that extend beyond biomass production.

From a soil security perspective, assessing soil condition requires a more comprehensive approach. This framework emphasises soil multifunctionality, provision of multiple services, and resilience against diverse threats, providing a more complete understanding of how secure a soil is in its physical state. Critically, soil security extends beyond biophysical domains to incorporate socioeconomic and political dimensions that influence how soil is valued, managed, and protected. These five dimensions, Capacity, Condition, Capital, Connectivity, and Codification, must all be fulfilled for soil to be considered secure. Assessing these dimensions across soil's various roles requires appropriate indicators and contextual interpretation.

This paper proposes indicator classes guided by the soil security framework to move from narrow agricultural-focused soil health concepts toward holistic understandings of soil that recognise diverse soil functions, services and the broader societal intersections with soil necessary for ongoing protection against threats.

Additionally, the paper aims to identify and discuss potential indicators that characterise the intrinsic nature of soil itself independent from its roles. Recognising and quantifying these intrinsic indicators would draw attention to the need to conserve and protect the soil not only for utilitarian functions but also as unique, irreplaceable entities within the biosphere.

In developing soil monitoring policies, there is a need for a collective understanding on how indicators are defined and interpreted. This means moving beyond vague "soil health" concepts to explicitly specify what the indicator is used to measure whether for biophysical or other dimensions of soil. Soil policy cannot rely on ambiguous metrics that fail to articulate what aspect of soil they actually indicate if we want to make a lasting impact with how soil is governed.

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# A Pedogenon Approach to Delineating Soil Districts across Europe

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**ABSTRACT**

With the recent adoption of the Soil Monitoring and Resilience Law by the European Parliament, the establishment of soil districts has become crucial to address soil degradation, which affects approximately 70% of Europe. Soil districts are defined as management zones that account for soil and environmental variability while remaining practical to implement, ideally at the administrative level.

Building on the recent proposal by Wadoux et al. (2024) to map soil districts in several European countries, an important question arises regarding the continuity and consistency of these districts across national borders. In parallel, soil districts have already been delineated in Australia using the pedogenon framework. This approach is based on mapping areas with similar quasi-stable soil-forming factors, defining soil geographical units not by the spatial variation of their properties - which may be sensitive to human activities - but by the spatial variation of environmental drivers. The underlying assumption is that similar soil-forming conditions lead to similar soils.

In Australia, soil districts were mapped by assessing similarities among pedogenons while applying spatial constraints to ensure the resulting units are both representative of soil diversity and practical for management decisions (Styc et al., 2025). The present study aims to replicate this methodology using the recently developed global pedogenon map (Francos et al., 2025), focusing on its application to Europe. Particular attention will be given to the challenges posed by the continent's intensive land use and management practices.

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# A Decade of Soil Security: From Concept to Global Action

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**ABSTRACT**

A decade after the conception of *Soil Security*, we can now clearly see how this once-aspirational idea has matured into a global framework placing soil at the centre of sustainability discourse. The Soil Security framework - built around five interlinked dimensions of *capacity, condition, capital, connectivity, and codification* - has evolved into a practical and dynamic tool connecting soil functionality to human prosperity and planetary health. It has deepened our understanding of how *pedogenons, genosoils,* and *phenosoils* interact to sustain soil resilience and ecosystem performance.

This presentation celebrates the *scientific, policy,* and *practical advances* achieved under the Soil Security paradigm over the past ten years. It will illustrate how the framework has begun to influence soil policy principles, guide governance strategies, and inform on-the-ground assessment across diverse climatic, economic, and management contexts.

Looking ahead, the next phase of Soil Security demands translation from concept to coordinated *national* and *regional strategies* that are both effective and affordable. Innovations in *digital soil assessment, proximal sensing, soil phenotyping,* and *data-driven governance* now make it possible to link local measurements with global indicators in real time - enabling low-cost, field-based monitoring and more responsive management.

As we enter the next decade, the opportunity lies in uniting *science, policy,* and *communities* under a shared ambition: to secure the world's soils as *living infrastructure* fundamental to food, water, and climate security, and the maintenance of biodiversity and ecosystem function. The long-term vision is bold yet achievable - *a global convention on soil security*, underpinned by actionable national strategy.

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# Quantifying Soil Security under Climate Change: Integrating Digital Soil Mapping and the Soil Security Assessment Framework

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**ABSTRACT**

Climate change is one of the most significant global challenges, with far-reaching impacts on the environment, economy, and society. Elevated temperatures, altered precipitation patterns, and extreme weather events affect terrestrial ecosystems, especially soils, a vital yet often overlooked natural resource. Changes in these climate variables can significantly alter soil properties, reduce functional capacity, and ultimately threaten soil security, which is a concept that integrates the sustainable management and protection of soils to maintain ecosystem resilience and human well-being.

This ongoing study applies the Soil Security Assessment Framework (SSAF) proposed by Evangelista et al. (2023) to evaluate how climate change affects soil security across New South Wales, Australia. The SSAF quantifies and maps the ability of soils to perform functions across each of the five dimensions (capacity, condition, capital, connectivity, and codification) of soil security. Here, only the capacity and condition dimensions are assessed. A baseline period (1971-2000) was used to model soil indicators and functions over time, which provides a foundation for forecasting future changes under projected climate scenarios.

Using the genosoil (inherent capacity) and phenosoil (current state) concepts, spatial layers of key soil indicators, including soil organic carbon, pH, cation exchange capacity, and bulk density, were generated through digital soil mapping with a Quantile Regression Forest model. The model achieved satisfactory performances, with $R^2$ values of about 0.6 for most indicators. Based on the genosoil and phenosoil layers, soil functional capacity and condition were assessed for the baseline period.

The next stage will predict changes in soil capacity and condition under future climate scenarios to identify emerging threats to soil security. These outcomes will contribute to the development of adaptive soil management strategies, inform policy decisions, and support the long-term goal of sustaining soil security in ongoing climate challenges.

**Keywords:** Soil Security, Climate change, Digital soil mapping, Soil security assessment framework

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# Legislation in Australia working for soil security (LAWSS)

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**ABSTRACT**

Soil governance plays a critical role in securing soils globally, a necessity accounted for under the codification dimension of the Soil Security Assessment Framework (SSAF). While soil policy encompasses principles and actions adopted by governing bodies to protect soil functions and services, soil governance has historically been neglected compared to water and atmospheric governance. Policy is codified into binding actions through laws and regulations. However, the codification dimension, defined as quantifying and monitoring policies and legislation related to soil security, is currently hindered by a lack of standardized quantification tools. The absence of quantitative metrics undermines efforts to secure soils at national and international levels, especially since existing legislation is often complex and lengthy and may focus narrowly on threats such as pollution or erosion, lacking comprehensive coverage of the 23 soil roles defined in the soil security framework.

This paper presents a novel framework for quantifying the completeness of soil security regulation for Australia, designed for integration with the other SSAF dimensions. The analysis employs semantic text comparisons between the 23 defined soil security roles (functions and services) and a corpus of Australian legislation and court decisions.

The methodology leverages Large Language Models (LLMs) to encode textual data into vector representations, using cosine similarity metrics to measure the semantic distance between legal texts and soil security roles. To ensure the retrieved documents are specifically relevant to soil, a composite similarity score is calculated, assigning 80% weight to the soil security role similarity and 20% to the similarity with an extended definition of soil policy. Expert validation, using a modified intercoder reliability method, was applied to the most similar documents to assign a binary score (relevant/not relevant) based on whether the document explicitly or implicitly referred to a given soil activity.

We demonstrate how the approach highlights role-specific coverage, reveals gaps and overlaps across jurisdictions, and supports prioritisation of legal review. The workflow is open, scalable, and designed to integrate with other SSAF dimensions, providing a foundation for longitudinal monitoring of soil-relevant governance. Using specific case studies, we discuss the further steps needed to constrain the spatial component of legislation, another aspect underrepresented in research.

This application of advanced text analysis opens new avenues for quantifying the SSAF codification dimension. By providing quantitative metrics for policy completeness, this framework can help stakeholders measure interventions, guide research questions, and highlight where legislation needs improvement, especially when soil agency may be subjectively interpreted or overlooked.

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# Towards a Global Convention to Secure Soil

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**ABSTRACT**

Despite its enormous importance and contributions, soil has been historically undervalued and often overlooked. To address this gap, the Soil Security Assessment Framework was recently developed to provide a comprehensive approach for quantifying the multifaceted roles of soil, including its functions, services, and resilience toward threats, across the five dimensions: capacity, condition, capital, connectivity, and codification. Together, these roles and dimensions operationalise soil security by translating soil's biophysical, socio-economic, and governance contributions into comparable metrics. Building on the Soil Security Assessment Framework, Aroura: the Soil Security Think Tank, was recently established to develop principles and policy recommendations aimed at securing soil globally. In this context, the promotion of a Global Convention to Secure Soil stands as an essential instrument to translate growing awareness into binding global cooperation; ensuring that soil is recognised, valued, and safeguarded as the living foundation of all terrestrial systems. By recognising and preserving soil diversity, preventing loss of functionality and services, decreasing threats to soil integrity, and ensuring the sustainable use of soil, an international treaty to secure soils would elevate soil's visibility on the global stage. This presentation outlines Aroura's aspirations and a practical pathway towards achieving a Global Convention to Secure Soil.

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# The Global Pedogenon Map: Combining and Spatialising the Factors of Soil Formation

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**ABSTRACT**

This study presents the development of a global pedogenon map, which classifies soil units based on similarities in their formation processes while excluding anthropogenic effects, at a high spatial resolution of 90 m. Designed for use by scientists, land managers, and policymakers, this map classifies distinct soil units —called pedogenons—based on key soil-forming factors, including parent material, climate, soil organisms, relief, and inherent soil properties. This study employs a combination of principal component analysis (PCA), non-metric-multidimensional-scaling (NMDS), and an unsupervised classification technique (K-means clustering) to capture the full range of soil formation processes across diverse landscapes of the world yielding an unbiased, globally applicable classification. The global pedogenon map enables soil capacity and condition monitoring on a global scale. This foundation is crucial for future identification of "least disturbed soils" to serve as a References for any soil around the globe. By integrating this dataset with broader environmental data, the global pedogenon map supports global efforts to enhance soil security and monitor environmental changes.

**Acknowledgments**

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# Components of a national soil security strategy for sustainable soil use and management

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## ABSTRACT

Soil security lies at the heart of resilient agricultural production, climate adaptation, and ecosystem sustainability, yet soils globally are under mounting pressure from degradation, land-use change, and climate extremes. Addressing this challenge demands integrated national strategies that embed soil in policy, economics, social governance, and knowledge systems. We present a robust vision for national soil security by refining five generic policy frameworks: Integrated soil security monitoring and assessment, soil-centric land use planning, economic valuation of soil services, comprehensive soil threat prevention and restoration, and stakeholder engagement and stewardship. We propose that an effective national soil security strategy should establish harmonised monitoring systems using advanced indicators to inform policy and practice at all levels. Land use planning should be reoriented to recognise soil as a critical natural capital asset, supported by zoning and regulatory mechanisms that prevent conversion of high-value soils and incentivise regenerative practices. Embedding economic valuation in policy through mechanisms such as payment for soil services can align market incentives with public goods, and thereby foster investment in soil conservation. Prevention and restoration frameworks should integrate climate - smart technologies, locally adapted regenerative practices, and targeted interventions against erosion, salinisation, and nutrient decline. Finally, governance and stewardship models—anchored in participatory, adaptive, and equity-driven approaches—are critical for sustaining momentum, ensuring accountability, and leveraging collective action. Together, these policy pillars chart a pathway for nations to transition from siloed, reactionary responses to proactive, anticipatory stewardship, with soil security concept as a foundation for food security, biodiversity, and climate resilience. Scholarly evidence and recent international initiatives underscore the urgency and practicality of this integrative approach, setting a new standard for soil security strategy at the national scale.

**Keywords:** soil policy, soil strategy, sustainable soil management, land use planning

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# European Union advances in soil protection with the Soil Monitoring Law, the Mission Soil and the Carbon farming

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**ABSTRACT**

In Europe, soil health is facing emerging challenges that require innovative solutions and policy interventions. We acknowledge that 62% of the European Union (EU) soils are not in healthy condition, while we face serious challenges such as climate change, food security, biodiversity loss, and socio-economic pressures. The severity of these issues is evident in the fact that soil erosion is unsustainable for around ¼ of the EU territory, carbon stocks in soils are declining, nutrients are depleting, and emerging contaminants can pose a serious threat to soil and human health. The costs of soil degradation in the EU may reach up to 70 Billion Euros per year, highlighting the urgent need for action. To address these challenges, the EU has put in place many policies for agro-environmental protection since 2000, including soil protection. The European Green Deal, launched in 2020, has set an ambitious roadmap to make the EU the first carbon-neutral continent with a modern, competitive, and resource-efficient economy.

This increased focus on soil health has led to the development of new policies and initiatives, such as the recent adopted Soil Monitoring and Resilience Law, which aims to establish a common framework for monitoring and assessing soil health. After a two-year legislative process, the Soil Monitoring Law has been definitively approved by the European Parliament in October 2025. The Law will establish a comprehensive and harmonized, yet flexible, framework for monitoring soil health, with criteria for healthy soils, and establish non-binding, sustainable targets for each soil descriptor. The EU Soil Observatory will support the implementation of the law through a range of actions, including the development of the EU Soil Health Portal, updating the LUCAS Soil Module, and the provision of technical guidance documents. The Law marks a significant step towards implementing effective soil protection policies in the EU and has put the aspirational target of achieving healthy soils by 2050. Furthermore, the Soil Mission, which aims to set up 100 Living Labs to promote sustainable land and soil management in urban and rural areas, will play a crucial role in achieving the objective of healthy soils by 2050. With an estimated investment of nearly €1 billion until 2028, funded research projects under the Soil Mission are expected to reverse soil degradation through action on the ground, underpinned by the development and monitoring of a set of indicators. In addition to these initiatives, the Carbon Removals and Carbon Farming (CRCF) regulation is the first EU volunteer framework for certifying carbon removals and carbon farming. This regulation will monitor, report, and verify carbon removals, soil emission reduction, and biodiversity benefits, providing a new opportunity for farmers and other stakeholders to contribute to climate change mitigation.

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# Connecting Soils and Consumers - The Regulation of Undefined Food Label Agricultural Sustainability Claims in Australia

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**ABSTRACT**

Governance frameworks are stakeholder operated interacting instruments and processes (Kooiman, 2016) performing various functions. Functions can include *inter-alia*, defining e.g., sustainable agricultural terms, metrics, outcomes, potentially connecting consumers to sustainable agricultural practices, and verifying 'sustainable' information displayed on food labels. Verification can both update relevant soil metrics and 'sustainably farmed' food label representations, based on how soil responses to agricultural practices. Food labels can encourage transformative change (Parker et al., 2021), increasing demand for sustainable agricultural products.

This paper examines Australia's food label governance framework, focusing on the regulation of undefined sustainable agricultural claims. It explores what protects consumers from false 'sustainably farmed' claims and considers how consumers and all stakeholders could be better connected to sustainable agricultural practices through revising the labelling governance framework structure.

Consumers cannot know or easily access information to ensure the sustainability of agricultural produce. Certification schemes can connect consumers to farming practices, promoting the importance of soils. In Australia, generally, soils are not part of certification schemes. Further, soil sustainable agricultural practices that benefit soil health are not communicated to consumers via food labels.

This paper argues a revised overarching food label governance structure can ultimately better connect consumers (and all agri-food stakeholders) with sustainable agricultural practices promoting greater recognition of, and demand for, sustainable Australian agricultural produce.

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# Soil Genotype and Cultural Diversity in Jeju Island, Korea: Linking Soil Security with Societal Heritage

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**ABSTRACT**

Jeju Island (1,846 km²), located at the southernmost tip of Korea, has long remained geographically and culturally isolated from the mainland, fostering distinctive cultural identities and agricultural practices. Even within the island, marked regional variations in customs had been closely linked to its pedogenic diversity. While most of Jeju's soils are volcanic, the narrow belts of the upper northern and far western zones possess dark brown non-volcanic soils that are relatively fertile, supporting crops such as rice, garlic, cabbage, and barley—forming historically prosperous communities. In contrast, the rest regions, dominated by volcanic ash soils, exhibit low fertility and bulk density but high organic matter, cation exchange capacity, phosphate adsorption, and porosity, giving rise to poorer agricultural settlements. Cultural expressions have mirrored this soil divide. Weeding songs in fertile zones are short and cheerful, whereas those in infertile volcanic areas are longer and plaintive. Dolmens and ancient relics occur exclusively in fertile soil regions, and ancestral rites differ according to land inheritance systems shaped by soil productivity. Likewise, seeding practices—furrow sowing versus broadcasting—reflect soil constraints and adaptation. These patterns demonstrate that soil characteristics profoundly shape cultural landscapes, reinforcing the nexus between soil genotype and societal phenotype. However, modern management—through fertilizers, pesticides, and mechanization—has homogenized soil productivity ("phenosoils"), eroding traditional soil-linked cultural diversity. This study underscores the vital connection between soil security and cultural heritage.

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# ADVOCATING FOR SOIL SECURITY: "FIRST CATCH YOUR HARE"

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**ABSTRACT**
**Individual Presentation or as a Panel Contributor**

It is more than a decade since the concept of Soil Security was developed as a new soil-centric, scientifically based, interdisciplinary framework for addressing multiple global challenges. Since 2013, its proponents have committed significant effort to its promotion, through specialised forums and publications. The establishment in 2024, of a new Global Soil Security Think Tank, Aroura, has accelerated this promotional effort and supported the production of a number of new papers and outreach products, to help explain and gain acceptance of the concept. While progress has been made and aspects of the soil security construct are drawing greater attention in some quarters, we are a long way from achieving the paradigm shift required to change national and international policy approaches to soil.

Currently the dominant paradigm understood and accepted by the majority of soil stakeholders and influencing the development of soil policy and strategies at the local, national, regional and and international level, is that of soil health. Soil health is recognised within the soil security concept as soil condition, i.e. only one of the dimensions of soil requiring policy attention. But with the level of attention to soil health growing, an even greater advocacy effort will be needed to convince policy makers to embrace the more comprehensive concept of soil security.

Thinking about this challenge, I am reminded of the famous expression, dating back to the 1700's "first catch your hare'. There are many explanations of its origin, and quite a number of variations ("first catch your fish/first catch your carp/first catch your stag"), but most attribute it to an instruction in a recipe by Hannah Glasse, the writer of an early cookery book-"The Art of Cookery. Made plain and Easy", published in 1747. Some argue it came from a medieval latin treatise, which included the phrase "and the common folk say that you must first catch your stag and after it has been caught, skin it"

Whatever its origins, it became a catch cry and is used to this day, to suggest the need to act methodically, step by step, to achieve an objective.

There are myriad/multiple goals built into the approach advocated by the designers of soil security, but the fundamental objective here is to gain acceptance of the concept of soil security, as THE, not A, basis for soil policymaking.

But even that isn't the first step.

As a long-standing advocate for soil and someone who has spoken often in national and international forums about the challenge of soil advocacy, I believe we have not yet reached the threshold of 'soil awareness' or 'soil consciousness", in the wider community that is necessary to "sell' the more sophisticated and strategic idea of soil security to policy-makers.

There remains an enormous task of advocating for soil before real traction can be achieved for soil security. 'First catch your hare' means, in the first instance, ongoing/intensified effort to achieve one of the key missions of the IUSS since its founding, "to promote global understanding of and engagement with soils and their protection'. It is no coincidence that the IUSS Strategic Plan 2021-2030 elevated this broad aim into a more purposeful, simple goal and made its number one strategic objective the "improvement of soil consciousness'. Halfway through the life of the Plan, it remains as urgent and vital a task as ever.

I do acknowledge that gains have been made- that the subject of soil is moving up policy agendas. I spoke at length about this at the Soils for our Future' Conference in Winnipeg in July, 2025, in a keynote address entitled 'The Changing Landscape for Soil Advocacy' and if time permits in this session, I will be happy to elaborate.

On this subject, I was interested to see that at this 23rd World Congress of Soil Science, there is a session entitled *'Soil Literacy for all: transforming global awareness into engagement and impact through collective action".* We all need to contribute to expanding 'soil literacy/soil consciousness" but doesn't the References to 'transforming global awareness'' also cause us to recall the 'first catch your hare' phrase? How can we talk about transforming global awareness into engagement and impact through collective action, if we haven't yet achieved global awareness of the value of soil, of the services it provides and the need to protect this precious resource?

I am not preaching pessimism. Just being realistic about getting in place the foundations for policy change.

And I should add that even though I argue the need for a broader soil advocacy effort to underpin the campaign to advance soil security, these actions can be taken in parallel- the one reinforcing the other. There are many avenues and new opportunities emerging for this to happen, at the national level, in regional fora and multilateral settings. I will be pleased to identify these in my presentation.

# Development of a Canadian Soil Strategy

**ABSTRACT**

The Soil Conservation Council of Canada is working collaboratively with numerous stakeholders to develop a Canadian Soil Strategy. The Strategy will be an **agriculture industry-led** framework and plan for collective action to maintain and enhance the agricultural soils in Canada, with an immediate view (by 2030) and longer-term view (by 2050). Some current work on the strategy are setting major objectives, identifying goals and priority actions for the agriculture industry and expanding current activities, while reducing duplicative efforts and increasing efficiency. A desired outcome of the strategy is to foster the agriculture industry's long-term commitments towards soil health.

The ongoing development of the strategy has involved seeking partners to help lead the development as well as sourcing resources to assist in the work required to generate a well thought out and comprehensive strategy. Work to date has focused on engagement with multiple stakeholder to gather input on what components/topics should be included in the strategy, reviewing similar strategies from other national jurisdictions, examining existing resources that highlight the need for a coordinated
national strategy.

This talk will highlight some of the successes and challenges that have come about during the initial phase of the strategy development, provide a summary of what stakeholders have been said is required in the strategy and a brief highlight of the current contents of the strategy.

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# Climate change intensifies phosphorus limitation in rice systems

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**ABSTRACT**

Phosphorus (P) availability is emerging as a critical but underrecognized constraint on rice production under climate change. Although elevated atmospheric $CO_2$ can stimulate crop growth, its long-term effects on soil P supply remain uncertain, particularly when warming occurs simultaneously. Here we synthesize evidence from long-term free-air $CO_2$ enrichment experiments and a decade-long field manipulation combining elevated $CO_2$ with in situ warming in a typical paddy-upland rotation system to examine how climate change alters P bioavailability in rice soils. Across experiments, soil available P showed little change initially but declined substantially over time, decreasing by more than 20% under long-term $CO_2$ enrichment alone and by 32-54% under warming or combined $CO_2$-warming treatments. These declines were accompanied by higher soil C:P ratios and increasing transfer of P into less bioavailable forms. Mechanistically, elevated $CO_2$ promoted organic P accumulation and enhanced P removal through harvest, whereas warming further intensified P depletion by strengthening Fe–organic carbon associations and microbial immobilization, despite initially stimulating P mineralization. Together, these aboveground-belowground processes reduced the capacity of soils to replenish plant-available P under sustained climate forcing. The results show that climate change can progressively weaken the soil P supply base required to sustain rice production, and that warming may intensify this risk beyond the effect of elevated $CO_2$ alone. These findings highlight an emerging challenge for future food production and underscore the need for adaptive nutrient management to maintain yield stability under changing climatic conditions.

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# Climate Change Effects on Rice Yield, Nutritional Health and the Free-Air $CO_2$ Enrichment Platform Innovation

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**ABSTRACT**

Rice paddies sustain more than half of the world's population, yet their responses to climate change remain a major uncertainty for future food security and human health. Based on long-term free-air $CO_2$ enrichment (FACE) experiments, we synthesized recent progress in understanding how elevated $CO_2$ reshapes rice productivity, grain quality and paddy ecosystem research capacity. First, we found that indica rice shows a 2- to 3-fold stronger yield response to elevated $CO_2$ than japonica rice. This contrast is mainly explained by the ability of indica rice to maintain nitrogen uptake, avoid photosynthetic down-regulation, and build a sufficient carbon sink in panicles. These findings led to a new conceptual framework in which enhanced nitrogen acquisition promotes carbon gain and high yield under elevated $CO_2$, enabling more accurate assessment of global rice yield responses and their spatial heterogeneity. Second, elevated $CO_2$ was shown to decrease key nutrients in rice grains while increasing grain arsenic accumulation. Mechanistic evidence indicates that nutrient dilution and altered plant water and nutrient transport reduce mineral concentrations, whereas elevated $CO_2$ enhances arsenic mobilization and bioavailability in flooded soils. These changes may aggravate hidden hunger and arsenic-related health risks among rice-dependent populations. Third, related work demonstrated that the $CO_2$ fertilization effect on rice yield is not necessarily sustained over multiple generations. Using FACE experiments, together with DNA methylation and transcriptome analyses, the study showed that multigenerational maternal $CO_2$ exposure alters rice nitrogen uptake, biomass and yield responses, highlighting the need to incorporate long-term $CO_2$ exposure into crop models. Finally, to overcome limitations of previous FACE platforms, we developed a third-generation FACE facility that can simultaneously simulate elevated $CO_2$ and whole-ecosystem warming under open-field conditions. This platform provides critical experimental capacity for evaluating rice production, nutrition and ecosystem resilience under future climate scenarios. Together, these advances support climate-smart strategies to increase rice yield, safeguard grain quality and reduce health risks in a high-$CO_2$ world.

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# From Soil to Grain: Organic Farming Improves Micronutrient Bioavailability

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**ABSTRACT**

Zinc (Zn) and iron (Fe) are essential micronutrients for human health, yet their deficiencies remain widespread globally. Agronomic biofortification of crop grains through improved farming practices offers a sustainable solution to enhance dietary micronutrient intake. This presentation combines findings from a long-term field experiment and a global meta-analysis to assess how organic and conventional farming systems influence Zn and Fe concentrations and bioavailability in crops.

Field data were obtained from the Glenlea Long-Term Crop Rotation Study (2011–2020), Canada's oldest continuous comparison of organic and conventional farming. Two fully phased crop rotations—annual (wheat–flax–oat–soybean) and annual-perennial (wheat–flax–alfalfa–alfalfa)—were evaluated. Organic farming significantly increased grain Zn concentration in most years, while Fe concentration remained unchanged. Grain Zn was also higher in the annual-perennial rotation in seven of ten years. Phytate concentrations were ~35% lower in the annual-perennial rotation under organic management, leading to reduced phytate/Zn and phytate/Fe molar ratios and improved micronutrient bioavailability. However, these nutritional benefits were associated with lower grain yield due to limited phosphorus (P) availability in organic systems, particularly following alfalfa. Compost addition improved yield but increased phytate levels, reducing Zn/Fe bioavailability.

To contextualize these results globally, a meta-analysis of 54 peer-reviewed studies (322 paired observations) compared organic and conventional systems across cereals, legumes, and vegetables. Organically grown crops contained on average 14.2% higher Zn concentrations (95% CI: 9.7–19.0%, $p < 0.001$), while Fe concentrations were generally similar, except under wet conditions (>850 mm annual precipitation), where Fe increased by 14.5%. However, organic systems showed a 24.7% lower yield (95% CI: –31.2 to –17.6%, $p < 0.001$), particularly in cereals grown in arid regions.

Together, these findings demonstrate that organic and diversified crop systems can enhance Zn bioavailability and, under specific conditions, Fe content, but often at the expense of productivity. The results highlight the need for integrated nutrient management—particularly phosphorus optimization—to balance the trade-off between crop yield and nutritional quality. Further research on micronutrient bioavailability mechanisms is essential for developing farming systems that advance both food security and human nutrition.

# Mycobacterium vaccae: The Interconnection between Soil Health and Human Health

**Winfred Espejo[1*], Camila Espinoza-Mendoza[1], Mauricio Schoebitz[1], José Celis[2], and Marco Sandoval[1]**

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**ABSTRACT**

*Mycobacterium vaccae* is a non-pathogenic saprophytic bacterium widely distributed in soils rich in organic matter. Its study has gained relevance due to its role in the interconnection between soil health and human health, within the conceptual framework of Planetary Health. This systematic review analyzed scientific publications (2000–2025) retrieved from databases such as PubMed, Scopus, Web of Science, and Cochrane, selected under PRISMA criteria and evaluated using validated methodological quality tools.

In soil environments, human exposure to *M. vaccae* occurs primarily through inhalation of soil particles, dermal contact, and indirect ingestion, being more frequent in rural settings and reduced in urban areas, where a "microbial deficit" has been observed. The identified immunological effects include the promotion of regulatory T cells and the reduction of systemic inflammation (Xiao et al., 2024). In the neurobiological context, exposure to M. vaccae enhances serotonin production, reduces neuroinflammation, and increases stress resilience (Ghosh, 2024). Animal studies and preliminary clinical trials report benefits in anxiety, depression, asthma, and atopic dermatitis (Ghosh, 2024).

Public health implications highlight the need to restore soil biodiversity and promote contact with natural environments through biodiverse green spaces and regenerative agricultural practices. Climate change, pollution, and soil degradation threaten M. vaccae populations, with potential adverse consequences for global health.

In conclusion, *M. vaccae* represents a key microorganism at the soil–human interface, with growing evidence supporting its immunological and neurological benefits. Preserving its natural habitat and ensuring adequate exposure to beneficial microorganisms should be integrated as preventive and well-being strategies in the 21st century.

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# Improving soil organic carbon sequestration through conservation tillage incorporating legume-based crop rotations

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## ABSTRACT

Conservation tillage combined with legume-based crop rotations (CT-LB) has gained global recognition as a climate-smart agricultural practice for its potential to enhance soil organic carbon (SOC) sequestration. However, the synergistic effects and underlying mechanisms by which CT-LB promote SOC accumulation remain unclear. This study conducted a global meta-analysis, utilizing data from 86 field trials across 78 publications, to examine interaction effects of CT and LB on SOC sequestration. Results showed CT and LB individually increased SOC by 5.25% and 2.21%, while CT-LB led to a synergistic 9.76% increase compared to traditional tillage with non-legume rotation (TT-TL). SOC enhancement under CT-LB was strongly correlated with total nitrogen (TN, $R^2$=0.73), soil aggregates >0.25mm ($R^2$=0.89), alkaline phosphatase ($R^2$=0.89), and light fraction organic carbon ($R^2$=0.94). Mechanistically, CT-LB improved SOC through: (1) increasing TN (+18.28%) and lowering C:N ratio (-12.22%) to enhance residue input and decomposition, (2) stimulating microbial and enzyme activity (+15–20%), and (3) promoting aggregation (+14.5%) that physically protects carbon. Site-specific conditions strongly influenced outcomes: warmer regions with initially low TN (<1 g/kg), low SOC (<10 g/kg), and high bulk density (>1.3 g/cm³) showed the most positive effects. Sub-group analysis confirmed that CT-LB significantly improved SOC particularly under compacted soils, lower fertility, and higher mean annual temperature/precipitation, while responses in cold regions (<9°C) were negligible. Across scenarios, CT-LB could increase global SOC sequestration by 0.06–0.19 Mg $ha^{-1}$ $yr^{-1}$ in the 0–20 cm layer if widely adopted. The integration of legume root systems and microbial secretions further facilitated micro- to macro-aggregate formation, encapsulating SOC against degradation. Discussion emphasized that while CT alone can sometimes elevate bulk density and limit nodulation, its combination with LB offsets such drawbacks by improving soil porosity, nutrient cycling, and microbial necromass stabilization. Importantly, the synergistic effect was larger than the sum of individual practices, underscoring the interactive benefits of combining reduced soil disturbance with legume diversification. Limitations included reliance on replication-based meta-analysis due to missing variance data, and conversion factors for SOC/BD in some studies, which may reduce precision. Nonetheless, this comprehensive synthesis demonstrates that CT-LB represents a practical, scalable strategy for enhancing SOC, mitigating climate change, and sustaining soil fertility. Conclusion: adopting CT-LB can substantially increase SOC storage, particularly in nutrient-poor, compacted, or warm environments, and should be prioritized within global conservation agriculture expansion.

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# Managing domestic trade for food security with environmental and economic equity in China

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## ABSTRACT

Balancing food security with environmental sustainability is a central challenge for large agrarian economies undergoing rapid structural change. China provides a critical case, having experienced a pronounced northward shift of grain production and intensifying domestic grain trade over the past four decades. Using provincial data from 1980–2020, we quantify how interprovincial grain flows redistribute land, water use, nitrogen pollution, and greenhouse gas (GHG) emissions between producing and consuming regions, and we assess future trajectories to 2060.

We combine a cost-optimization trade model (CHINAGRO) with provincial statistics on grain production, consumption, and socio-economic variables to simulate interprovincial flows of rice, wheat, and maize. We then estimate embedded virtual cropland, virtual water, nitrogen losses ($NH_3$, NOx, $NO3^-$), and net GHG emissions ($CO_2$, $CH_4$, $N_2O$ minus soil and biomass carbon sequestration). Fixed-effects panel models and structural equation models are used to identify climatic and socio-economic drivers, and an SSP2-based scenario to 2060 is coupled with a nitrogen–carbon credit framework to explore environmental tax and subsidy transfers.

From 1980 to 2020, interprovincial grain trade in China increased more than fivefold, while production shifted from south to north. This reorganization transferred environmental burdens—virtual cropland, blue–green water use, and nitrogen pollution—from increasingly urbanized southern consumers to northern producers. Despite these pressures, net GHG emissions embedded in traded grain declined by ~41%, driven by the expansion of relatively low-emission maize systems and cropland carbon sinks in northern regions. Projections indicate that by 2060 northern China will further consolidate its role as the national "granary", with trade volumes and associated virtual resource transfers continuing to rise; however, embedded nitrogen and net GHG emissions are projected to increase as trade expands.

Under a stylized nitrogen–carbon credit scheme, we estimate that grain-consuming regions would need to transfer on the order of US$81 billion annually by 2060 to internalize production-stage nitrogen and GHG externalities. The findings highlight the importance of integrating domestic trade, spatial production shifts, and environmental accounting when designing eco-compensation, agricultural modernization, and dietary transition policies.

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# Omics analysis reveals the antagonistic mechanism of foliar zinc-selenium application and its impact on wheat grain quality

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## ABSTRACT

Zinc (Zn) and selenium (Se) are essential trace elements for human health. However, approximately 17.3 % and 50–100 million people worldwide are at risk of Zn and Se deficiency, respectively, primarily due to low concentrations of these elements in staple foods. Importantly, projected future rises in atmospheric $CO_2$ concentrations will increase carbohydrate content while decreasing protein content in C3 crops, further reducing Zn concentration in wheat grains. Foliar application is an effective agronomic strategy to improve human micronutrient nutrition, but the interaction mechanisms during Zn-Se co-application and their impact on the co-biofortification of grains remain unclear.

This study integrated field and pot experiments with subcellular fractionation, transcriptomics, and proteomics to analyze the Zn-Se interaction mechanisms across multiple scales: organ allocation, subcellular distribution, and molecular regulation. It also investigated the response of grain proteins to Zn-Se accumulation under Zn-Se co-biofortification. The research revealed: First, compared to Se application alone, Zn-Se application reduced grain Se content by 37.5 %, indicating an antagonistic interaction between the two elements. Concurrently, the allocation proportion of Se in leaves increased by 7.8 %. Subcellular distribution showed Zn driven Se sequestration in leaf cell walls and soluble fractions. The addition of Zn reversed the grain Se concentration and the leaf-to-sheath translocation factor from positive to negative correlation. Transcriptome analysis indicated that co-application regulated the expression of genes involved in Zn/Se/S/P-related transport and metabolic pathways, forming a regulatory network that likely drives Se subcellular compartmentalization and impedes its translocation to grains. Second, despite the antagonistic interaction, optimizing the application concentration (0.4 % $ZnSO_4 \cdot 7H_2O$ + 0.0021 %–0.0024 % $Na_2SeO_3$) effectively compensated for this antagonism, enabling Zn-Se co-biofortification while ensuring grain Se content remained below the toxic threshold (<1.0 $mg \cdot kg^{-1}$). The biofortified grains achieved an organic Se proportion as high as 96.7 %, and both whole grain products and milled flour could meet the estimated daily Zn and Se intake requirements for adults. Proteomic analysis further revealed that differentially expressed proteins in Se metabolism, S metabolism, and amino acid metabolism pathways collectively responded to Zn-Se accumulation in grains. Furthermore, foliar application upregulated the expression of reactive oxygen species scavenging related genes (e.g., *SOD*, *GST*), enhancing the antioxidant capacity of wheat. Additionally, the potential ecological risk index (RI) for the incorporation of Zn-Se enriched straw was less than 150, indicating a low risk level.

In summary, this study elucidates the multi-scale mechanisms of Zn-Se antagonism and provides a theoretical foundation and molecular targets for optimizing Zn-Se co-biofortification technology. This approach integrates directly into conventional wheat production, ensuring yield without high cost or specialized equipment. It aligns with the United Nations' second Sustainable Development Goal of ensuring global food security and improving nutrition by 2030, offering a technical pathway and theoretical support to address nutritional security challenges under global change.

**Keywords:** Biofortification; Selenium speciation; Zinc accumulation; Transcriptome; Proteome

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# Occurrence, Properties and Sustainable Management of Degraded Upland Soils Under a Changing Climate in the Philippines

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**ABSTRACT**

Soil is a multifunctional resource, but humans have focused almost exclusively on managing soil for biomass (food) production, thereby causing rapid soil degradation and reducing its ability to provide the multifunctionality that underpins human and planetary health (Kopittke et al., 2025). Soil degradation is a major ecological problem that impacts environmental health and food security in the Philippines. This is particularly true for many upland areas where the poorest Filipino farmers, who are also the most vulnerable and most food insecure, are living and farming (Roa, 2007). Soil degradation has not only decreased crop productivity on these lands but also caused environmental problems such as soil erosion, floods, siltation in lowlands and water bodies, and the drying up of drinking water sources. Uplands, which comprise about 60 percent of the country's land area, are defined as undulating and steep lands that range in elevation from near sea level to about 1000 m elevation. This definition is geomorphological and clearly separates the flat lowlands from the elevated uplands (Asio et al., 2024).

As in other SE Asian countries, the major processes of soil degradation in the Philippines are water erosion, chemical degradation, and physical degradation. Water erosion is primarily caused by agricultural practices, particularly overgrazing and deforestation; chemical degradation is almost exclusively the result of improper management of cultivated arable lands; and physical degradation is mainly due to agricultural activities. The major factors that cause soil degradation include deforestation, overgrazing, agricultural practices, industrial activities, mining, and waste disposal. The increased frequency of strong typhoons due to climate change significantly contributes to soil degradation, aggravating the effects of the wet tropical climate with an annual rainfall ranging from about 1,000 mm in the south to more than 4,000 mm in mountainous areas, particularly along the eastern coast of the archipelago (Asio et al., 2009; Asio et al., 2024).

Degraded upland soils in the Philippines can be grouped into three types based on the landforms where they occur: a) the fragile young soils from recent volcanic materials (mostly Andisols and Inceptisols) on higher elevations and rugged topography; b) the highly weathered but more resilient soils (Ultisols) on the more stable slopes on the lower elevations; and c) the poorly to moderately developed soils (mostly calcareous) on sedimentary hills along coastal plains (Inceptisols and Mollisols). Degraded upland soils have several physical and chemical fertility problems that limit their use for crop production, the most common among which are strongly acidic/alkaline pH, low organic matter content, low nutrient status, and shallow solum. The typical plant species in marginal and degraded uplands that can be used as indicator plants are Cogon grass (*Imperata cyclindrica*), Bugang or Talahib (*Saccharum spontaneum*), Carabao grass (*Paspalum conjugatum*), Hantutuknaw (*Melastoma malabathricum*), and Guava (*Psidium guajava*), which is almost always present in marginal uplands.

Agroforestry is widely considered the sustainable form of land use for marginal and degraded upland soils. An innovative form of agroforestry, which the Philippine government has formally endorsed to rehabilitate degraded lands, is *Rainforestation Farming*, which is the planting of native tree species available in the locality together with food crops (Asio, 2017). Contour farming, although not widely practiced by upland farmers, is another technique effective in conserving rainwater and reducing soil losses from surface erosion. Contour farming practices are classified into vegetative barriers and physical barriers. Vegetative barriers include contour hedgerows, natural vegetative strips, contour fences, and contour composting, while physical barriers include contour furrows, contour bunds, contour rock walls, and bench terraces. Fertilization with a combination of chemical fertilizers and manure, especially chicken manure, is widely practiced in many areas, particularly where poultry farms are located (Asio et al., 2024).

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# Bio-Composts and Soil Microbiomes under a One Health Approach: Assessing Microbial Shifts and Antimicrobial Resistance in an Ex-Situ Pilot Study

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## ABSTRACT

The continuous use of synthetic fertilizers and pesticides has led to serious environmental and health concerns, including soil degradation, biodiversity loss, and pollution. In this context, bio-composts derived from organic waste are increasingly recognized as sustainable alternatives that enhance soil fertility and microbial activity. However, their potential role in the dissemination of antimicrobial resistance (AMR) remains poorly understood.

This study evaluated the effects of two bio-compost formulations (pelleted and powdered) on soil microbial communities and the occurrence of antibiotic-resistant bacteria (ARBs), adopting a One Health approach that integrates human, animal, and environmental health perspectives. Experiments were conducted in an *ex-situ* pilot system consisting of three tanks containing untreated soil, soil plus pelleted bio-compost, and soil plus powdered bio-compost. Samples were collected over one year (T0–T4) and analyzed using molecular and cultivation-based approaches.

DNA quantification and 16S rRNA sequencing revealed an overall increase in bacterial biomass following bio-compost application, reaching up to $1.1 \times 10^6$ ng DNA/kg soil. Taxonomic analysis showed that bacterial groups such as *Paenibacillus*, *Brevibacillus*, and *Corynebacterium*, originating from the compost, became dominant over time, partially replacing native soil taxa. Despite these compositional shifts, the treatments did not significantly alter the abundance of ARBs. Resistant isolates were identified through cultivation on selective media containing ampicillin or trimethoprim, followed by susceptibility testing to ten antimicrobials. Although trimethoprim-resistant strains were detected in the bio-composts, no significant increase in ARB populations was observed in treated soils compared with controls.

These findings, interpreted within the One Health framework, indicate that bio-compost application enhances microbial proliferation and soil biological quality without promoting AMR spread in the short term. Nevertheless, the detection of resistant strains within compost underscores the importance of continuous AMR surveillance across interconnected ecological and agricultural systems. Understanding these soil–microbiome–health interactions is essential for ensuring the safety, sustainability, and resilience of bio-based fertilization practices in the face of global change and food security challenges.

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# Risks of Wheat Yields Reduction Under Future Climate Extremes

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## ABSTRACT

Climate change increasingly threatens global wheat production, with rising temperatures and shifting precipitation patterns reducing yields. Understanding future spatiotemporal patterns of and key climate drivers of wheat yield is critical for sustainable development. However, previous studies often overlooked complex nonlinear relationships among multiple climate factors. Here, we combined APSIM-wheat with Random Forest-SHAP to capture both the wheat growth process and complex, non-linear relationship and threshold effects between yield and climate factors. A comprehensive dataset consisted of 15 national long-term experiments located in three major wheat production regions of China was used for this purpose. APSIM models showed strong predictive accuracy across all regions. Using the validated crop models, we projected future wheat yield and analyzed the response to extreme climate events under various scenarios. Results indicated that wheat production would stagnate or decline in the mid- to long term, varying by climate scenarios and regional condition. Yields ranged from 4.0-7.2 t ha-1 under low-emission and 2.5-6.5 t ha-1 under high-emission scenarios. In the long term, the gap between low- and high- emissions scenarios was expected to widen. Under high-emissions scenarios, yields in Northwest China decreased by 30-40 % by 2099 due to heavy precipitation and cold extremes, making it the most vulnerable areas. In Yangtze River Basin, yields decreased by 19-36 % as hot extremes and heavy precipitation, while in North China Plain, they decreased by 17-25 %, mainly from hot extremes. Extreme climate events had significant nonlinear and threshold effects on yields. This study emphasizes the need for greater consideration of region-specific strategies and provides a foundation for targeting management practices to maintain food security and enhance long-term resilience to future multiple climate disasters.

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# Towards Sustainable Rice Cropping Systems in a Changing Climate

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**ABSTRACT**

Agriculture's environmental footprint is expected to expand as population, income, and demand for resource-intensive foods rise. Climate change further compounds these pressures by threatening crop yields while accelerating greenhouse gas emissions. Rice production exemplifies this tension: paddy systems feed over half of the global population yet generate nearly one-fifth of agricultural methane emissions, a gas with around 27 times the warming potential of $CO_2$. In this talk, I will present recent work on management and breeding strategies designed to sustain rice yields while lowering emissions. Drawing on field experiments, modelling, and global data syntheses, I will examine how water management, cultivar choice, and fertilizer regimes together shape methane and nitrous oxide fluxes in paddy ecosystems. I will emphasize the strong role of biophysical and socioeconomic context, underscoring the need for region-specific recommendations rather than one-size-fits-all solutions. I will then highlight evidence that integrated practices (including improved irrigation, straw management, and machinery) could raise global yields and deliver considerable social and economic benefits, but may paradoxically increase area- or yield-scaled emissions if implemented without parallel investments in mitigation. Finally, I will outline approaches to future-proof rice systems, including strategies to capture the $CO_2$ fertilization effect and reduce vulnerability to climate extremes. Together, these findings illustrate both the potential and the limits of current mitigation pathways, and the challenge of reconciling food security with climate goals.

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# Preservation of Patterned Ground in Permafrost Non-Affected Soils: Evidence form the Central Apennines (Italy)

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**ABSTRACT**

Sorted patterned ground represents a morphological soil surface characteristic associated with a polygenetic origin. Among the proposed mechanisms, differential frost heaving caused by repeated freeze-thaw cycles in soils influenced by the permafrost active layer or subjected to seasonal freezing is considered the most possible, while other processes are mainly theoretical. This study investigated the genesis and preservation of patterned ground in the upper Majella Massif (Central Apennines, Italy) through integrated analyses of soil and air temperatures, as well as soil morphological, mineralogical, and physicochemical properties. Mean annual ground surface and winter equilibrium temperatures suggested that permafrost was absent at a depth <2 m, although this does not exclude the presence of a deep, relict form of a shallow permafrost in past climatic phases. Therefore, the observed patterned ground may be features originating from shallow permafrost during ancient climatic phases, which have been preserved by mechanisms affecting the superficial soil horizons. Principal Component Analysis revealed that the preservation of relatively larger patterned ground is primarily controlled by soil texture and mineralogy, particularly the content of 2:1 clay minerals which enhance water retention and promote frost heave. The results suggested that preservation is confined to the uppermost soil horizons, where freeze-thaw cycles induce miniature (diameter of the sorted circle is 3 to 7 cm) patterned ground development. In addition, wind-driven snow redistribution, which leads to patchy snow cover and limited thermal insulation of the soil, contributes to the preservation of permafrost. Under these conditions, freezing of water-saturated soil may generate sorting of rock fragments, and repeated superficial freeze-thaw cycles result in the formation of the miniature patterned ground. This study highlights how past environmental conditions, soil properties, ongoing freeze-thaw processes, and local microclimatic factors interact to shape patterned ground in mid-latitude mountain environments.

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# The link between soil security and one health

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**ABSTRACT**

Soil provides multiple and diverse functions (e.g., the provision of food and the regulation of carbon), which underpin the health of animals, humans, the environment and the planet. However, the world's soils face existential challenges. To this end, the concept of Soil Security was developed. In parallel, the concept of One Health likewise works across the human–animal–environment interface, highly relevant for the goals of Soil Security. In this review, we evaluated the roles which both the Soil Security and One Health concepts have served in the literature between 2012 and 2023 and explore the potential linkages between both concepts. We outline that both concepts are used in disparate fields, despite considerable overlap in aims and objectives. We highlight the Soil Health concept as a potential connector between Soil Security and One Health. Overall, we argue that both Soil Security and One Health are highly complementary fields of scientific inquiry with solid leverage for translation into policy and practice. However, there is a need to define One Health dimensions, as has been done for Soil Security. We advocate for a biosphere-focused framework to collectively make progress toward the 2030 Sustainable Development Goals and other global existential challenges.

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# Global wheat soil metagenomes reveal dryland cropping systems as microbial genomic hotspots

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**ABSTRACT**

Wheat is one of the most important grain crops globally and is unique among major cereals in that it is extensively cultivated across both irrigated and rainfed agroecosystems. This wide environmental distribution provides a valuable yet underexplored opportunity to investigate how contrasting water management shape soil microbiomes at a global scale.

We first assembled a global wheat soil dataset comprising 145 sites from 22 countries, representing both irrigated and rainfed production systems. Comparative metagenomic analyses revealed that cropping environment (irrigated versus rainfed) was the second most important factor influencing both taxonomic and functional diversity of soil microbiomes, following geographic location. Notably, rainfed wheat soils harboured a substantially greater number of unique microbial genes than irrigated soils, suggesting enhanced genomic diversification under long-term water limitation.

Building on these global patterns, we focused on Australian rainfed wheat systems, which represent the largest rainfed wheat-growing region in the world. We established an Australian wheat soil bank consisting of samples collected across the continent. Deep metagenomic sequencing (~4Tbp data) generated a comprehensive gene catalogue containing 337 million non-redundant genes, more than double the size of the current global soil gene catalogue (159 million genes, Bahram et al 2018). Remarkably, fewer than 10% of genes overlapped between the two catalogues, highlighting the exceptional genomic novelty and functional uniqueness of Australian rainfed wheat soils.

Functional profiling revealed strong associations between microbial genes linked to plant drought resilience and site-level annual rainfall, indicating microbial adaptation to long-term water limitation and potential roles in crop stress tolerance. Soil pH across Australian dryland wheat systems exhibited a relatively narrow range (5.6–8.3) yet showed significant positive correlations with both taxonomic and functional diversity of the soil microbiome. These patterns align with observations from global native soils (Bahram et al 2018), where pH is a dominant driver of microbial diversity, and the native systems span a much wider pH range (2.5–7.5).

Collectively, this study demonstrates that long-term rainfed wheat systems harbour highly distinctive and functionally specialized soil microbiomes shaped by water availability and soil physicochemical constraints. Dryland cropping soils as a globally significant reservoir of microbial genomic novelty and provide a foundation for leveraging soil microbiomes to enhance drought resilience and sustainability under future climate change.

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# Optimizing Mineral Nutrition to Improve Soybean Yield and Quality under Elevated $CO_2$

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**ABSTRACT**

The rapid rise in atmospheric carbon dioxide ($CO_2$) concentration is a principal driver of global climate change. Since the Industrial Revolution, anthropogenic activities have continuously elevated atmospheric $CO_2$ levels, generally enhancing crop productivity through the $CO_2$ fertilization effect. Legumes often exhibit a stronger yield response to elevated $CO_2$ ($eCO_2$) than cereals, primarily because symbiotic nitrogen (N) fixation alleviates N limitations, enabling legumes to better exploit the increased carbon availability. However, meta-analyses indicate that the actual yield enhancement of soybean under $eCO_2$ conditions is substantially lower than model projections, suggesting that its yield potential in future $CO_2$-enriched environments remains constrained. Emerging evidence points to limitations in non-N mineral nutrients as key factors restricting legume growth and symbiotic nitrogen fixation under $eCO_2$. Supporting observations include consistent declines in soybean seed concentrations of essential micronutrients such as iron and zinc under $eCO_2$. Moreover, effective nodule development and nitrogen fixation in soybean require adequate supplies of multiple mineral elements, including magnesium, iron, and sulfur. Taken together, these findings suggest that improving the availability of non-N nutrients in agricultural soils may represent a promising approach to further enhance soybean yield and nutritional quality in future high-$CO_2$ environments.

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# Characteristics of paddy soil: specifics in dynamics in organic carbon cycling

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## ABSTRACT

Rice paddy ecosystem has the dual functions of carbon (C) source and C sink. Therefore, it is of great significance for ensuring China's food security and achieving the goal of "C neutrality", by controlling the C sequestration and greenhouse gas mitigation of paddy soil. In recent years, research focused on the process and mechanism of soil organic carbon (OC) turnover in paddies has been carried out all over the world. This review summarized the process and mechanism of soil C sequestration in paddies from the aspects of sources, transformation, stabilization, and regulation technics of OC, and propose strategies to deal with the "C neutrality". The main source of soil OC was rice straw, root, rhizodeposits, microbial assimilation C and organic fertilizer. After the input of exogenous organic materials into soil, the decomposition and mineralization were first controlled by the dissolution process of OC. The microbial mineralization of the dissolute OC was closely related to soil moisture condition, nutrient content and its stoichiometric ratio, microbial activity, and other factors. Apart from emitted soil OC, the remaining part of inputs was mainly anabolized to form living microorganisms and microbial residues, which were finally fixed in soil protecting by aggregate, organo-mineral colloidal complex, and necromass (amino sugar). Paddy soils in China have significant effect on C sequestration. In the recent 40 years, research data showed that the soil OC content of the subtropic paddy soil has been increased by 60% under the implementation of multiple managements such as irrigate and fertilizer application and straw returning. It had positive effect on achieving "C neutrality" by adopting the managements of increasing C sequestration and mitigating greenhouse gas emission. These managements included optimizing the combination irrigate and fertilizer application and straw returning, establishing an ecological compensation mechanism for C emission reduction, and promoting the inclusion of the rice farming system into the "C trading market". Therefore, it is necessary to clarify the mechanism of C sequestration function in paddy fields, improve the accuracy of accounting and forecasting C neutrality, accelerate the development of C neutralization technology in paddy field in future research, which provide scientific and technological support for achieving the "C neutrality" strategic goal in advance.

**Keywords:** Paddy soil; soil organic carbon; soil carbon sequestration; greenhouse gas emission mitigation; irrigate and fertilizer management; carbon neutrality

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# Deciphering the Role of Ethylene Signaling in Endoplasmic Reticulum Stress Response and Crop Resilience

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**ABSTRACT**

Global climate change-induced adversities such as high temperature, drought, and salinity severely threaten crop productivity and food security by triggering endoplasmic reticulum (ER) stress—a condition where the protein folding capacity of the ER is overwhelmed, activating a conserved unfolded protein response (UPR) to restore cellular homeostasis. Failure of this response can lead to cell death. While the phytohormone ethylene is implicated in regulating ER stress responses, the underlying molecular mechanisms remain elusive. Our previous work identified a complex interplay between ethylene signaling and the key ER stress transducers bZIP28/bZIP60, which mediate the UPR. Genetic analysis using multiple mutants including *bzip28/60 ctr1-1*, *bzip28/60 ein2-5*, and *bzip28/60 ein3 eil1* revealed that ethylene signaling components CTR1, EIN2, and EIN3/EIL1 modulate plant sensitivity to ER stress, both in concert with and independently of bZIP28/60. To dissect the ethylene-specific regulatory network, we performed transcriptomic profiling of WT, *bzip28/60*, *ein3 eil1*, and *bzip28/60 ein3 eil1* seedlings under ER stress. Comparative analysis of differentially expressed genes (DEGs) confirmed that bZIP28/60 primarily control the upregulation of most ER stress-responsive genes. Gene Ontology (GO) enrichment analysis in WT highlighted significant induction of processes including stress response, signaling transduction, and programmed cell death, while processes like translation and photosynthesis were suppressed. Importantly, we identified a subset of ER stress-responsive DEGs dependent on EIN3/EIL1, which were enriched in similar stress- and cell death-related pathways. Cluster analysis pinpointed a group of genes potentially coregulated by ethylene and ER stress pathways, showing expression patterns consistent with EIN3/EIL1-dependent regulation under stress. From this cluster, we identified key candidate genes—including *ORE1/ORS1*, *DIN2*, *SEN1*, *bZIP1*, *ABI1*, *NYC1*, and *NYE1*—with known roles in senescence, energy metabolism, stress adaptation, and chlorophyll degradation. These genes were validated as ER stress-inducible via quantitative real time-PCR. Our findings propose a dual model whereby ethylene fine-tunes ER stress responses: (1) through EIN3/EIL1 interaction with bZIP28/bZIP60 during UPR, and (2) via a parallel, bZIP28/60-independent pathway that modulates cell death and stress adaptation. This study provides novel targets for enhancing crop resilience against climate-associated abiotic stresses, contributing to the sustainable soil–plant systems under changing environments.

**Keywords:** endoplasmic reticulum stress, ethylene signaling, unfolded protein response, abiotic stress, cell death, crop resilience, transcriptomics.

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# Effects of Quinoa Cultivation on Greenhouse Gas Emissions and Soil Properties in Different Saline-Alkali Ecosystems

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**ABSTRACT**

Saline-alkali soils is an important globally distributed ecologically fragile area, and the coupling relationship between vegetation restoration and carbon cycle processes has become a research hotspot in global change studies. Quinoa is a high-biomass crop with cold resistance, drought resistance, and salt-alkali tolerance, exhibiting great potential for application in the ecological restoration of Saline-alkali soil. However, the carbon allocation mechanism and greenhouse gas emission (GHGs) characteristics of quinoa under different saline-alkali environments remain unclear. This study was conducted in the Saline-alkali soils of Inner Mongolia and Dongying. The in-situ GHGs fluxes in quinoa-cultivated plots and non-cultivated plots (control) were monitored using the field static dark chamber method. Meanwhile, soil samples were collected to analyze soil chemical properties, including pH, total nutrients, water-soluble salts, dissolved organic carbon, available nitrogen and so on. The aim of this study was to reveal the influence mechanism of quinoa cultivation on GHGs and soil fertility in Saline-alkali soils. The results showed that: 1) Quinoa cultivation significantly increased greenhouse gas emissions in Saline-alkali soils. Compared with the control, the global warming potential was increased by up to 30.99%. However, there was no positive correlation between greenhouse gas emissions and quinoa biomass, and the plot with the highest biomass was not the one with the highest emissions; 2) Quinoa cultivation significantly improved the soil nutrient status of Saline-alkali soils. The contents of total soil nutrients were significantly increased, and the content of soil water-soluble salts was effectively reduced, alleviating the degree of soil salinization; 3) Correlation analysis indicated that GHGs were mainly regulated by soil pH, total nitrogen, available nitrogen, and dissolved organic carbon contents, and changes in soil chemical properties were the key factors driving the variations in greenhouse gas emissions. This study is the first to systematically clarify the carbon cycle effects and soil improvement potential of quinoa in different saline-alkali ecosystem, providing a scientific basis for the synergistic management of vegetation restoration and greenhouse gas emission reduction in Saline-alkali soils, and enriching the theoretical research on the carbon cycle of saline-alkali ecosystems in arid and semi-arid regions.

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# Revisiting Food Security in the Context of Climate Change: How Co-Occurring Heatwaves and Atmospheric Lead Deposition Jeopardize Crop Production

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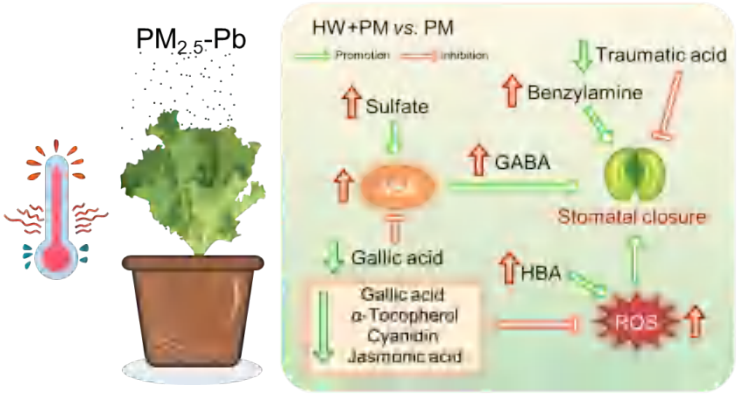
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## ABSTRACT

Industrial development, urbanization, and agricultural activities have significantly increased anthropogenic atmospheric heavy metal pollution, with metals mainly adhering to fine particulate matter ($PM_{2.5}$, $PM_{10}$), which is transported over long distances via atmospheric deposition, ultimately contaminating plant leaves and soils, thereby polluting terrestrial ecosystems. Studies have shown that atmospheric deposition is the primary source of heavy metal accumulation, particularly lead (Pb), in leafy vegetables near urban and industrial areas, with Pb on $PM_{2.5}$ entering plant leaves and inhibiting crop productivity. In the context of global warming, the frequency, duration, and intensity of heatwaves (HW) in terrestrial ecosystems are increasing. Heat stress leads to stomatal opening for heat dissipation, which may further promote the infiltration of $PM_{2.5}$ into plant tissues, exacerbating crop yield loss and amplifying health risks through the food chain.




Our results demonstrate that, under HW conditions, atmospheric $PM_{2.5}$-Pb exposure significantly reduces lettuce yield and nutritional quality, including soluble sugars, soluble proteins and amino acids. In contrast, $PM_{2.5}$-Pb exposure or heat stress alone did not adversely affect lettuce (*Lactuca sativa* L.) yield or induce stomatal closure. However, under heatwave conditions, $PM_{2.5}$-Pb markedly decreased stomatal conductance and net photosynthetic rate. The combined effects of HW and $PM_{2.5}$-Pb further triggered dynamic stomatal closure and reactive oxygen species accumulation, leading to chloroplast deformation and impaired photosynthetic activity. Metabolomic analyses elucidated the molecular mechanisms by which $PM_{2.5}$-Pb regulates stomatal closure under heatwave stress and highlighted the consequent losses in lettuce yield and nutritional quality driven by stomatal dysfunction.

Collectively, these findings underscore that climate change can indirectly intensify human health risks transmitted through the food chain by amplifying the ecotoxicity of existing pollutants. Increasingly frequent HW may therefore render current pollution regimes more damaging, imposing a “double hit” on crops during critical growth stages and threatening the stability and resilience of global food systems. Addressing these emerging challenges requires moving beyond isolated approaches to climate mitigation or pollution control, and instead adopting an integrated “climate–pollution–health” framework to safeguard crop productivity and human health under a changing climate.

**Acknowledgments**

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# Low-Carbon Wheat Program: Integrating Soil Quality and Soil Carbon Dynamic into Life Cycle Assessment

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**ABSTRACT**

There is an urgent need for sustainable economic transitions in response to global warming and climate change impacts. Despite its role in global food security, agriculture significantly contributes to greenhouse gas (GHG) emissions. Quantifying GHG emissions from agricultural systems is primordial to support climate change mitigation strategies and the transition toward low-carbon food production systems. The wheat carbon footprint is primarily driven by nitrogen fertilisation, field emissions, and soil management. However, a conventional Life Cycle Assessment (LCA) approach does not account for soil characteristics, attributes and special variability. The soil is treated as a static background condition, failing to account for spatial variability in soil attributes and their influence on carbon dynamics, productivity, and GHG emissions. This limitation constrains the identification of effective mitigation pathways and weakens the robustness of carbon-footprint baselines in agricultural assessments. The Low-Carbon Wheat Program (LCWP) in Brazil is a science-based research, development, and innovation initiative aimed at promoting climate-smart and regenerative practices across wheat production systems. The program integrates soil and crop management, sustainability indicators, and life cycle assessment within a harmonised framework focused on reducing greenhouse gas emissions and improving environmental performance. The framework integrates chemical, physical, and biological soil attributes, as well as soil carbon dynamics, into Life Cycle Assessment (LCA). The LCWP framework posits soil as a central analytical component of LCA rather than a contextual descriptor, enabling a more realistic representation of soil-driven processes within environmental assessments. Soil quality is characterised using chemical, physical, and biological indicators, which are integrated into management quality indices to represent soil functioning and conservation status. In parallel, soil organic carbon dynamics are explicitly modelled using RothC. This approach aims to establish a robust site-dependent carbon footprint baseline and promote the mitigation and removal of GHG through improved soil management and climate-smart production strategies. Moreover, the framework is designed to support measurement, reporting, and verification (MRV) requirements and to align with the findable, accessible, interoperable, and reusable (FAIR) data principles, thereby enabling scalability across regions and management contexts. This framework provides a structured basis for supporting decision-making in research, policy design, and value-chain strategies to accelerate the transition to low-carbon wheat systems.

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# Green recycling food waste management – a comparative case study in China

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**ABSTRACT**

Food waste is the world's dumbest environmental problem, accounting one-fifth of food getting wasted globally and with about ten percent of greenhouse gas emissions come from food waste worldwide. It has been a major challenge threatening global food security and environmental sustainability. Food waste recycling and repurposing are promising for lowering the environmental and economic burden of discarded food, facilitating agroecosystem sustainability. In this study, the economically developed and populous Taihu Lake region of China was selected as a research pilot to conduct life cycle assessment of food waste treatment scenarios in the region. Typical treatment scenarios are incineration, aerobic composting, and anaerobic digestion. The results showed that aerobic composting had the best environmental efficacy in most of the impact categories, including global warming, terrestrial acidification, freshwater eutrophication, human health, freshwater ecosystems, and terrestrial ecosystems. Anaerobic digestion ranked first in particulate matter absorption and photochemical ozone synthesis. Incineration has the worst results in all environmental impact categories. On the economic level both incineration and anaerobic fermentation resulted in higher costs, whereas aerobic composting was able to achieve an economic benefit of 96.07 CNY/t.

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# The compensation by elevated $CO_2$ for the impacts of warming yields a net positive overall effect of climate change on ecosystem services A global meta-analysis

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## ABSTRACT

The interactive effects of elevated $CO_2$ ($eCO_2$) and warming—two core drivers of global change—on terrestrial ecosystem services remain systematically underexplored. Our study synthesizes 2,619 observations from 257 studies across global cropland, grassland, and forest ecosystems to address this gap. Unlike previous analyses that often rely on unpaired factors, we exclusively included studies with paired factorial designs (encompassing control, warming, $eCO_2$, and their combined treatment). Our methodology yielded results that stand in clear contrast to those of earlier research. For instance, while both factors individually increased root biomass and soil respiration, their interaction reduced root biomass and showed no significant effect on soil respiration—a counterintuitive result likely stemming from unpaired factors comparisons, which our design avoids. Our results indicate that $eCO_2$ generally exerts positive effects on ecosystem services, largely compensating for the negative impacts of warming, leading to an overall positive net effect. Specifically, $eCO_2$ enhanced crop yield and plant productivity by improving water use efficiency and photosynthetic rates. While warming alone potentially stimulated photosynthesis, it did not translate into significant yield benefits and even risked reducing productivity. Under interaction, the positive effects of $eCO_2$ compensated for the negative impacts of warming, resulting in significant yield increases. Furthermore, $eCO_2$ improved soil health and climate mitigation by enhancing water use efficiency, soil biodiversity, nutrient cycling, carbon sequestration, and plant nitrogen uptake while reducing reactive nitrogen losses. In contrast, warming had negligible overall effects on these aspects, and the interactive effects consistently aligned with the influence of $eCO_2$ alone. Critically, we found that the interaction between warming and $eCO_2$ is not simply additive, as often assumed. Instead, it shows as synergistic or antagonistic effects on key indicators like grain yield and carbon sequestration. This key finding provides new theoretical support for refining climate models and machine learning predictions.

**Keywords:** Climate change; Terrestrial ecosystem services; Food security; Interaction effect

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# Sustainable Management of Zinc in the Soil–Plant–Animal Continuum

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## ABSTRACT

As plants assimilate micronutrients from the soil, they serve as the primary conduit through which these elements enter the food chain. Zinc is a vital micronutrient that is indispensable for the physiological and metabolic processes of plants, animals, and humans. Although required in trace amounts, zinc deficiency is widespread in Indian agricultural soils, primarily due to intensive cropping systems, imbalanced application of macronutrient fertilizers, and inadequate incorporation of organic matter. These factors have adversely affected fodder productivity and nutritional quality, thereby influencing zinc status in livestock and humans. Adopting a **One Health** perspective, this study investigates zinc fertilization mediated changes in the soil–plant–animal continuum. A field-cum-animal study was conducted at Coimbatore district, Tamil Nadu, India, using a fodder crop under four nutrient management treatments *viz*., NPK control, NPK + 25 kg $ZnSO_4$ $ha^{-1}$ applied as basal, NPK + 0.5% $ZnSO_4$ foliar spray applied thrice at 10-day intervals, and NPK + 25 kg $ZnSO_4$ $ha^{-1}$ applied as basal combined with 0.5% $ZnSO_4$ foliar spray applied thrice at 10-day intervals. Dairy cow animals of uniform age were identified for the study. The fodder crop was grown and was fed to selected dairy cows continuously @ 20 kg/animal/day. The required amount of green fodder grown in each treatment plot was fed to the selected animals for 15 days for attaining stabilization. After the stabilization period, the milk sample was collected from dairy cows fed with and without zinc enriched super Napier fodder at weekly intervals for 5 weeks. The results of the experiment revealed that, application of NPK along with 25 kg of soil application of $ZnSO_4$ + 0.50% Foliar spray thrice at 10 days interval significantly improved the fodder yield by 12.5%, zinc content by 17.5% over NPK besides sustaining the Zn availability and improved the fodder quality. Feeding the dairy cows with Zn enriched fodder improved the milk Zn content by 9.6%. These findings support the effectiveness of zinc enrichment through combined soil and foliar zinc application as a practical solution to combat zinc deficiencies across the food chain. The findings offer important insights into the transfer and bioavailability of nutrients, particularly zinc, across the soil–plant–animal continuum and provide a practical framework for applying the One Health approach in agriculture, demonstrating how targeted micronutrient management can simultaneously enhance soil fertility, fodder quality, livestock nutrition, and ultimately human health outcomes.

**Key words**: Micronutrients, Zinc, Animal nutrition, Soil-Plant-Animal Continuum.

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# Remediation of Degradaged Coastal Soil Using Biochar and Pyroligneous Acid

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**ABSTRACT**

Coastal wetlands are referred to as “blue carbon” sinks due to high primary production and C storage capacity. However, ongoing degradation of these ecosystems reduces coastal carbon sequestration, threatening cultivated land availability and food security. Therefore, it is necessary to restore these degraded soils to ensure sustainable food production using eco-friendly technologies. Biochar and its by-product, pyroligneous acid (PA), have raised wide interests because of their multiple benefits in soil improvement. In this study, a wood waste derived biochar (WBC), composted biochar product (CBC), and PA were applied into a coastal saline soil collected from the Yellow River Delta to investigate the response of a commercial crop, okra (*Abelmoschus esculentus*) to their individual or combined applications using a 120-day pot experiment. Compared with the un-amended treatment, the WBC and CBC significantly increased the total biomass and pod yield of okra by 144%, 229%, 149%, and 392%, respectively. Similarly, PA increased the pod yield by 128%, but with little effect on the total biomass of okra. Compared with individual PA application, the co-application of PA and WBC or CBC significantly increased the biomass and pod yield of okra by 107%, 229%, 157% and 261%, respectively. Moreover, these amendments application increased the content of soluble protein and flavone of the pods, suggesting the improved nutritional quality. The increased plant growth and pod yield were mainly attributed to the enhanced nutrients availability (e.g., $NO_3^-$-N, Olsen-P) and improved soil properties (e.g., pH, exchangeable sodium). Additionally, increased microbial abundance and diversity, along with a shift in the rhizosphere bacterial community toward beneficial taxa, were identified as key factors driving these positive outcomes. Our findings demonstrate that co- application of biochar and PA is a practical and promising strategy for restoring productivity in degraded coastal soils, thereby supporting soil health and food security.

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# Beyond constant $CO_2$: Asymmetric day-night elevation, arbuscular mycorrhizal fungi, and intercropping dynamics shape plant physiology and productivity

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## ABSTRACT

**Background and Objectives**: Current research on elevated $CO_2$ ($eCO_2$) largely focuses on aboveground responses in simplified monocultures, neglecting critical belowground biotic interactions and the ecological reality of diurnal $CO_2$ fluctuations. This study addresses this gap by investigating the tripartite interaction between asymmetric day-night $eCO_2$ regimes, arbuscular mycorrhizal fungi (AMF) inoculation, and intercropping of nitrogen-fixing (fababean) and non-fixing (wheat) species.

**Methods**: Wheat (*Triticum aestivum*) and fababean (*Vicia faba*) were cultivated in monoculture and intercropping within controlled-environment chambers. Plants were subjected to inoculation with or without the AM fungus *Funneliformis mosseae* under four asymmetric $CO_2$ regimes: ambient ($aCO_2$; 400/450 ppm, day/night), daytime $eCO_2$ ($DeCO_2$; 550/450 ppm), nighttime $eCO_2$ ($NeCO_2$; 400/600 ppm), and full day-night $eCO_2$ ($D+NeCO_2$; 550/600 ppm). Key growth and physiological parameters were analyzed at harvest.

**Results**: Elevated $CO_2$ consistently increased the root-to-shoot biomass ratio and soluble sugars while decreasing tissue N, P, and K concentrations, leaf gas exchange, chlorophyll, soluble protein, and free amino acids. The physiological sensitivity to $eCO_2$ followed a distinct hierarchy: **$DeCO_2$ > $D+NeCO_2$ > $NeCO_2$ > $aCO_2$**. In contrast, the synergistic benefits of AMF colonization on host plants were maximized under **$D+NeCO_2$**, followed by $DeCO_2$ and $NeCO_2$.

**Conclusions**: The AMF–$eCO_2$ interaction differentially modulates plant performance in a host-specific and cropping pattern-dependent manner. Our findings demonstrate that **daytime $CO_2$ elevation drives physiological shifts, while synergistic plant-AMF benefits are greatest under sustained (day+night) $eCO_2$.** This underscores the necessity of integrating key biotic symbionts with ecologically realistic, asymmetric $CO_2$ scenarios to accurately forecast and manage agroecosystem productivity under future atmospheric conditions.

**Keywords:** Fababean, monoculture, mycorrhization, $N_2$-fixation, winter wheat

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# The evolution of assimilable elements in the soil, and in the Sorrento Lemon PGI during growth

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**ABSTRACT**

Plant uptake of elements (essential and beneficial, of unknown utility, or harmful) is a process that can vary seasonally due to fluctuations in environmental factors. Factors such as climate and human activity affect the bioavailability of soil elements and their absorption by plants, influencing the abiotic and biotic phenomena in the soil and the physiology of plants, both of which can be only partially interpreted.

Previously, Ruggiero et al. (2022) proposed multielement composition as an indicator of origin for the Sorrento Lemon (Femminello cv. Ovale di Sorrento) of Protected Geographical Indication (PGI). The PGI area (Sorrento Peninsula and Capri Island, southern Italy) is relatively small and has a rather homogeneous soil origin. However, significant seasonal variations in the concentrations of some elements have already been observed, making multielement signature less effective to distinguish local production from the others.

The research focuses on the multielement variability of Sorrento Lemon PGI. The accumulation of elements in lemons was observed in parallel with their bioavailability in the soil over two years (2024-2025) of production during fruit growth (autumn-winter that is a highly dynamic period for elements in the fruit and soil). This was done to identify the elements in mature fruit expected to be subject to minimal seasonal variability. This enables the identification of the elements most suitable for authenticating Sorrento Lemon PGI production and for preventing fraud related to its geographical origin.

Thus, to assess such variability, in a PGI lemon orchard of the municipality of Massa Lubrense, the bioavailability of more than forty elements was monthly assessed in soil, and in lemon sampled from autumn to winter at developmental stages: green, yellow-green, and yellow. The element bioavailability in the orchard was studied together with pedoclimatic characteristics and availability of water in the soil. The study of the element accumulation in lemon was supported by observing the evolution of the qualitative and biometric characteristics of the fruit during growth. The readily and potentially bioavailable elements in soil were extracted according to methods used in environmental analyses. All analyses were conducted using accredited methods. Elements were determined by ICP-MS, MS/MS, and OES. Data were statistically processed using univariate and multivariate methods.

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# Integrated Physiological and Microbial Mechanisms Underlying Cold Tolerance in Japonica Rice: From Root Function to Rhizosphere Ecology

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**ABSTRACT**

**Background and Objectives:**
Cold stress is a major abiotic constraint limiting rice productivity, particularly in high-latitude and high-altitude regions. While the detrimental effects of low temperature on above-ground physiology are well-documented, a comprehensive understanding integrating root system responses, rhizosphere microbial dynamics, and their collective impact on yield formation remains elusive. This research program systematically investigated the multi-faceted impacts of low-temperature stress, specifically low water temperature (Tw), on japonica rice. The objectives were to: (1) quantify the effects of low Tw during reproductive growth on photosynthetic production, nitrogen (N) uptake, and yield components; (2) elucidate the relationships between root physiological traits, phytohormone signaling, and panicle development under cold stress; (3) characterize the shifts in root morphology, physiology, and rhizosphere microbial communities (diversity, composition, and function) induced by low-temperature treatment at different growth stages (tillering, booting, combined); and (4) identify key microbial genes and pathways associated with cold response and their links to plant performance.

**Methods:**
Field experiments were conducted over multiple years (2015-2024) in Harbin, a cold-temperate region of Northeast China. Two japonica rice cultivars with contrasting cold tolerance—DN428 (moderately tolerant) and SJ10 (susceptible)—were used. A split-plot design was employed with low-Tw treatment as the main factor and variety as the sub-plot factor.
*Reproductive Stage Low-Tw Stress:* Plants were subjected to 17 °C Tw for durations of 3-15 days during reproductive growth (panicle initiation). Measurements included photosynthetic parameters (net photosynthetic rate Pn, leaf area index LAI, chlorophyll content), N concentration and uptake in different tissues, yield components, root vitality, xylem sap rate, root absorption surface area, antioxidant enzyme activities, and phytohormone (ABA, IAA, GA3, ZR) levels in roots, leaves, and panicles. Anther ultrastructure and pollen fertility were examined via microscopy.
*Multi-Stage Low-Temperature Treatment* : Treatments were applied at: Tillering stage (T1, 15 °C, 7 days), Booting stage (T2, 17 °C, 7 days), and a combination of both (T3). Controls (T0) received normal irrigation. Root morphological traits (length, surface area, volume), physiological activity (oxidation activity, xylem sap rate), root N accumulation, and biomass were measured. Rhizosphere soil was sampled at key stages for analysis of pH, organic matter (OM), total N (TN), total P (TP), available P (AP), and available K (AK). Metagenomic sequencing was performed on soil DNA to profile microbial community diversity, composition, and functional potential. Weighted Gene Co-expression Network Analysis (WGCNA) was used to identify gene modules and hub genes correlated with root traits and soil nutrients.

**Key Results:**
*Reproductive Stage Impact*: Low Tw during reproductive growth severely impaired N uptake, which decreased linearly with treatment duration. This led to reduced LAI and Pn, inhibiting normal panicle development. A significant decrease in seed setting rate and grain weight were the primary causes of yield loss. Despite increased spike N concentration at maturity, grain N yield declined (by 4 –47%). The cold-tolerant DN428 maintained higher N utilization efficiency and harvest index under stress than SJ10.
*Root-Panicle Relationships under Cold Stress*: Low Tw disrupted pollen development and reduced fertile pollen percentage. It significantly decreased the number of surviving panicle branches and spikelets, with a greater
impact on secondary than primary structures. DN428 maintained better anther development and panicle size. Its stronger cold tolerance was associated with higher root levels of zeatin (ZR) and auxin (IAA), which helped sustain root antioxidant enzyme activity (SOD, POD, CAT), vitality, and absorption surface area. This facilitated photosynthetic material transfer to support spikelet formation.
*Root and Rhizosphere Response to Multi-Stage Cold*: All low-temperature treatments (T1, T2, T3) significantly suppressed root morphological and physiological traits, with the combined T3 treatment having the most severe effect. DN428 consistently exhibited smaller declines than SJ10. Cold stress altered rhizosphere properties, increasing OM, TN, and TP but decreasing AP and AK. Microbial alpha diversity (Shannon index) was most significantly reduced at the full heading stage. Beta diversity analysis showed distinct shifts in microbial community composition under stress, especially for T3.
*Microbial Community and Functional Shifts*: Low-temperature treatment altered the relative abundance of key bacterial phyla (e.g., *Arthrobacter, Gemmatimonas*). *Actinomycetota* and *Euryarchaeota* were positively associated with positive root traits, while *Thermodesulfobacteriota* showed negative correlations. AP and AK were dominant drivers of microbial community structure. Metagenomic functional profiling indicated changes in pathways like "Carbon metabolism" and "Two-component system." Network analysis revealed that cold stress simplified microbial co-occurrence networks, particularly in SJ10.
*Identification of Key Genetic Elements*: WGCNA identified gene modules significantly correlated with root traits and soil nutrients. The MEbrown module, positively associated with root oxidation activity, contained hub genes *lacZ* (K01190, β-galactosidase), *fucK* (K00879, L-fuculokinase), and *rafA* (K07407, α-galactosidase), implicating galactose and pentose phosphate pathways in the cold response.
*Integrated Pathways to Yield Loss*: Structural equation modeling revealed variety-specific mechanisms. In DN428, yield loss under T2/T3 was primarily driven by cold-induced downregulation of key microbial functional genes (e.g., *lacZ, rafA, fucK*), leading to impaired rhizosphere nutrient cycling and subsequently suppressed root physiology and N accumulation. In SJ10, yield loss was more associated with a broader collapse of rhizosphere microbial community structure and diversity (reduced alpha diversity), which directly limited soil AP availability and root activity.

**Conclusions:**
This integrated research demonstrates that low-temperature stress impacts rice through a cascade of interconnected physiological and ecological disruptions. The cold-tolerant cultivar DN428 employs a strategy centered on maintaining root hormonal homeostasis and physiological activity, allowing for relative stability in panicle development. Its yield loss under severe cold is closely linked to the suppression of specific microbial functional genes critical for carbon and energy metabolism. In contrast, the susceptible SJ10 suffers from a more generalized degradation of rhizosphere microbial community structure and function, leading to a sharper decline in nutrient bioavailability and root performance. These findings highlight that enhancing cold tolerance in rice requires an integrated "gene –microbe –root function" approach. Future strategies should aim not only at improving plant intrinsic cold tolerance but also at fostering resilient rhizosphere microbiomes capable of maintaining metabolic activity and nutrient cycling under low-temperature stress.

**Keywords:** Japonica rice; Low-temperature stress; Root physiology; Nitrogen uptake; Rhizosphere microbiome;



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# Abiotic Dephosphorylation of Nucleotides by Manganese oxides

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**ABSTRACT**

Nucleotides constitute an important pool of organic phosphorus in natural environments, and their hydrolysis represents a crucial geochemical process that links biological activity and phosphorus cycling. Iron and manganese minerals, which are widely distributed and highly reactive, can catalyze the dephosphorylation of nucleotides, thereby influencing phosphorus cycling. In this study, the dephosphorylation of nucleotides by a series of manganese oxides was systematically evaluated, identifying α-$MnO_2$ as the most effective catalyst. Further investigation into the reactivity of α-$MnO_2$ toward nucleotides with different phosphorus stoichiometries revealed that acidic conditions promoted the dephosphorylation of adenosine triphosphate (ATP) and adenosine diphosphate (ADP), whereas adenosine monophosphate (AMP) remained resistant to dephosphorylation. High-performance liquid chromatography (HPLC) and attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy were employed to track the stepwise hydrolysis products and to elucidate the key interfacial complexation between nucleotides and the α-$MnO_2$ surface, thereby clarifying the catalytic mechanism of phosphoanhydride bond cleavage. These findings provide new insights into the abiotic transformation of organic phosphorus and highlight the potential role of manganese oxides in triggering phosphorus cycling under environmental conditions.

**Key words**: nucleotides; manganese oxides; phosphorus cycle; dephosphorylation

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# Leveraging Sulfate to Modulate Arsenic Accumulation in Rice

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**ABSTRACT**

Sulfate fertilization reduces arsenic (As) uptake in rice, but its dose-dependent mechanisms under flooded-drained conditions remain unclear. A pot experiment with sulfate doses revealed that 100 mg $kg^{-1}$ sulfate addition created the strongest reducing conditions, driving peak sulfate consumption and sulfide production. This enhanced FeS formation, sequestering As in solids and lowering porewater As. Consequently, grain As decreased by 48% at 100 mg $kg^{-1}$ sulfate addition, versus 26% at 200 mg $kg^{-1}$ sulfate addition. Thus, an intermediate sulfate dose optimizes microbial sulfate reduction and FeS-mediated As immobilization, minimizing grain As accumulation.

**Keywords:** Sulfate fertilization, Arsenic (As) accumulation, Flooded-drained conditions, Microbial sulfate reduction

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# Legacy soil information in the Northern Regions of Ghana: Implications for Integrated Soil Fertility Management (ISFM)

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**ABSTRACT**

**Introduction**

Soil fertility remains a challenge in Ghana and other sub-Saharan African countries. The major farming systems in the region are characteristically low input and rely heavily on inherent soil organic matter. Ghana has one of the lowest fertiliser application rates in the sub-region. This situation is worse in the northern part of Ghana (Debpuur et al., 2021) where the low-productive soils have negatively impacted on crop yields of smallholder farmers. Integrated soil fertility management (ISFM) practices which is premised on combining organic resources and inorganic fertilisers to combat soil fertility decline in combination with improved germplasm has been introduced as a credible technology for restoring soil fertility. This study was carried to provide basis for implementation of Integrated Soil Fertility Management in the Upper East, Upper West, North East and Northern Regions of Ghana.

**Materials and methods**

A total of 34 demonstration fields were delineated from 17 districts within the Upper East, Upper West, North East and Northern Regions. The polygon coordinates of the demonstration fields were taken using Geographic Position System (etrex 30 GPS). It was imported in the ArcMap 10.7.1 and edited into polygon features. These shapefiles were used for extraction of aggregated soil information (from 1980 to 2016) Google Earth Engine (GEE) and www.Soilhive.ag.

**Discussion**

The soil chemical properties obtained from legacy soil data indicate the low soil primary macro nutrients including organic carbon in the thirty-four communities of the four regions. The generally low primary macro nutrients of the intervention districts and communities require external source of nutrients for good crop growth indices and ultimately improved yields.

**Conclusion:**

The soil chemical properties of the project intervention districts are low in primary macro nutrients and external inputs in the form of organic and chemical fertilizers are needed to improve and sustain soil fertility. The concept of ISFM to improve soil fertility is therefore a justified management practice.

**Acknowledgments**

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# Soil Health-Driven Improvements in Tropical Fruit Production: Insights from a Vietnam "Living Lab"

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## ABSTRACT

Vietnam's fruit sector faces persistent constraints—including variable fruit quality, suboptimal yields, and stagnant farmer incomes—that limit competitiveness in high-value export markets. This study evaluates whether soil-health-based farm management, supported by improved diagnostics and targeted interventions, can enhance fruit production, quality, and sustainability across major tropical fruit systems. The work was conducted within the multi-year project Improving Quality of Tropical Fruit Vietnam, initiated in 2019 under the Vietnam Farmers' Union, which functions as a Living Lab to co-develop and demonstrate scalable solutions with farmers, advisors, and local authorities.

The central research question was: Can integrated soil health diagnostics and tailored nutrient management measurably improve fruit yield, quality, and shelf life in Vietnam's tropical fruit systems? To address this, crop- and site-specific baseline management plans were established across several provinces and updated annually. A dedicated soil testing laboratory was created, applying two complementary broad-spectrum analytical approaches: Near Infrared Spectroscopy (NIRS) and 0.01 M $CaCl_2$ soil extractions (1:10 soil:solution), followed by ICP-AES or ICP-MS for quantification of plant-available nutrients. NIRS calibrations were developed using large international datasets and validated prior to routine use. In Vietnam, NIRS prediction of soil organic carbon (SOC) showed excellent agreement with References measurements ($R^2$ = 0.96; RPD = 4.8; RMSEP = 0.13), with similarly strong performance for N-total, soil organic matter, clay content, and effective cation exchange capacity (ECEC). Measurements included plant-available macro- and micronutrients, bioavailable heavy metals, SOC, pH, soil texture, and water quality, complemented by monitoring of crop protection residues in soil and fruit. Diagnostic results revealed widespread soil acidity and low plant-available calcium and phosphorus as key constraints. Management interventions—such as optimized liming, vermicompost application, and calcium–phosphorus blends—were tailored accordingly. These interventions led to increased mango yields, reduced fertilizer costs, and improved fruit nutrient profiles (higher Ca, lower N). Mango shelf life improved by 4–10 days, and no pesticide residues were detected in mango fruits in the final project year. Water quality was generally adequate, though elevated iron levels and localized salinity posed risks for irrigation and production.

Overall, the findings demonstrate that soil-health-based management, combined with improved fertilization, water management, and integrated pest control, can substantially enhance fruit yield, quality, and shelf life in tropical systems. These improvements strengthen export potential to markets such as Europe, the USA, and Japan, while supporting farmer livelihoods and sustainability goals. The Living Lab approach provides a replicable model for Vietnam's wider fruit sector, and the broad-spectrum soil testing framework offers a robust basis for monitoring progress toward relevant Sustainable Development Goals (SDGs).

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# Reduced Protein Content under Elevated $CO_2$ Enhances Perfluorooctanoic Acid Bioaccumulation in Wheat

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**ABSTRACT**

Perfluorooctanoic acid (PFOA) contamination in agricultural soils poses a persistent and growing threat to food safety and human health. However, how rising atmospheric $CO_2$ concentrations reshape PFOA bioaccumulation in wheat, a major global staple crop, remains unknown. Here, we systematically examined the impacts of elevated $CO_2$ ($eCO_2$) on the fate of PFOA in soil–wheat systems under environmentally relevant contamination levels. Elevated $CO_2$ significantly reduced protein content and root protein exudation in wheat, thereby disrupting protein-mediated immobilization of PFOA in the rhizosphere and leading to an 8.8–12.4% increase in whole-plant PFOA accumulation.

At the root–soil interface, protein depletion impaired the formation of PFOA–protein complexes, compromising the protective function of the root epidermis. Simultaneously, cytosolic protein concentrations in roots declined markedly by 32.1–53.1%, substantially limiting intracellular sequestration of PFOA. As a result, PFOA translocation from roots to grains increased by 55.4–59.3%. These combined processes ultimately elevated PFOA concentrations in wheat grains by 12.2–29.4%, significantly amplifying the potential risk of human dietary exposure.

Collectively, our findings reveal that $eCO_2$-induced protein depletion across the soil–plant continuum drives a previously unrecognized enhancement of PFOA bioaccumulation in wheat. This study highlights the compounded risks arising from interactions between legacy soil contaminants and ongoing climate change, underscoring the necessity of integrating climate-driven physiological responses of crops into future soil pollution risk assessments and food safety management strategies.

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# Soil pH controls cropland $N_2O$ responses to rising $CO_2$

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## ABSTRACT

Human activities, particularly fossil fuel combustion, deforestation, and other land-use changes, have driven a substantial increase in atmospheric $CO_2$ concentrations, from 315 ppm in 1958 to 430 ppm in 2025[1]. Projections suggest these levels could reach 800 ppm by the end of the century[2]. Elevated atmospheric $CO_2$ ($eCO_2$) often stimulates photosynthesis in C3 plants and enhances carbon assimilation[3]. $eCO_2$ generally increases carbon input into soils, affecting both the production and consumption of nitrous oxide ($N_2O$)[4], the third most important greenhouse gas. However, the net impact of $eCO_2$ on $N_2O$ emissions from global cropland is uncertain, and the underlying drivers are poorly understood.

Here, we present integrated experimental and meta-analytical evidence showing that soil pH fundamentally regulates $N_2O$ responses to $eCO_2$. We show that the stimulatory effect of $eCO_2$ increases with soil pH, driven by two complementary mechanisms: greater carbon-fueled $N_2O$ production and reduced $N_2O$ consumption as soils acidify. By incorporating the $CO_2$–pH interaction, our ensemble of top-performing meta-analysis models projects that $eCO_2$ will increase $N_2O$ emissions from global croplands by an average of 3.1%, substantially lower than previous estimates (+29%)[5]. Our findings resolve key discrepancies in literature and provide a mechanistic framework to improve climate model projections and guide targeted mitigation strategies in agroecosystems under future atmospheric conditions.

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# Active soil microbiomes link urbanization and climate to zoonotic pathogen risk in Chinese cities

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## ABSTRACT

Urban soils host highly diverse microbial communities and serve as a critical biological interface linking environmental change to human health under the One Health framework. However, conventional DNA-based surveys cannot distinguish active, dormant, or dead microorganisms, potentially leading to overestimation of pathogen risk and obscuring the ecological processes governing zoonotic pathogen dynamics. Resolving the activity status of soil microbes is therefore essential for identifying true pathogen risk hotspots. Here, we characterized urban active soil microbiomes using PMA-enabled sequencing across 203 soil samples collected from 24 Chinese cities, spanning gradients of urbanization intensity, land-use types (arable land, urban forests, and parks), and climate conditions. By focusing on metabolically active microbial fractions, we examined how urbanization, land use, and environmental factors jointly shape the spatial patterns of potential zoonotic and priority pathogens in urban soils. Active microbial diversity was consistently 30–50% lower than total DNA-based diversity, yet showed pronounced compositional and ecological divergence, indicating that a limited subset of fast-responding taxa dominates real-time microbial activity. Urban soils harbored diverse active zoonotic pathogens, with distinct pathogen assemblages associated with different land-use types. Urbanization markedly increased the activity, detection frequency, and richness of rodent-associated pathogens, particularly within urban park soils, where detection rates approached saturation in megacities. Pathogen risk patterns were jointly driven by soil physicochemical properties, especially nitrogen forms, and urban socio-ecological intensity, while higher active microbial diversity was associated with reduced pathogen risk. Together, these findings demonstrate that active soil microbiomes, rather than total microbial presence, govern urban pathogen ecology, mediating the effects of climate and urbanization on zoonotic risk. By explicitly incorporating microbial activity, this study provides a mechanistic basis for microbiome-informed urban planning and targeted interventions aimed at enhancing urban resilience to emerging public health threats.

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# Harnessing machine learning to improve nitrogen loss predictions in agroecosystems

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## ABSTRACT

Understanding and predicting nitrogen (N) losses across diverse agroecosystems is essential for designing more sustainable management strategies. However, N losses vary substantially across soils, climates, and management practices, and occur through multiple pathways including leaching, runoff, and gaseous emissions. This spatial and temporal complexity makes robust quantification challenging and limits the transferability of management recommendations across regions. Process-based agroecosystem models provide a mechanistic framework for simulating soil–plant–atmosphere interactions and nitrogen transformations. Yet their application at broader scales is often constrained by intensive parameterisation requirements, structural uncertainty, and difficulties in calibration and validation across heterogeneous datasets. As agricultural monitoring expands and multi-source data become increasingly available, machine learning (ML) presents new opportunities to enhance predictive performance. This presentation explores how ML approaches can complement, rather than replace, mechanistic modelling. We assess key limitations in current process-based simulations of agricultural N losses and demonstrate how ML can enhance parameterisation, identify hidden patterns, and improve predictive performance across regions. We propose a hybrid modelling framework that integrates biogeochemical process understanding with data-driven learning, aiming to deliver more accurate, scalable, and decision-relevant tools for sustainable N management.

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# Soil health as a driver of yield patterns and management

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**ABSTRACT**

Managing soil health (SH) within agricultural fields sustains high yields while preserving essential ecosystem services. However, agriculture often focuses on soil chemistry (SC), while physical (SP) and biological (SB) aspects are neglected, compromising soil functions. In this study, we integrate these three dimensions to assess whether SH can explain yield variability and guide management decisions. In two commercial sugarcane fields in Southeast Brazil (42 and 40 ha), we delineated high- and low-yield zones from two years of yield and ancillary data, carrying a targeted soil sampling (15 and 9 samples) at 0–10, 10–20, 20–40 cm. Principal component analysis (PCA) was used to evaluate yield variability in relation to 32 soil attributes, selecting a minimum dataset. Using the Soil Management Assessment Framework (SMAF), we generated SC (pH, potassium), SP (clay, bulk density) and SB (organic carbon, β-glucosidase activity) indices and integrated them into a soil health index (SHI) ranging from 0 (poor) to 1 (excellent). PCA showed that SC had the 12 most influential attributes for PC1, while SP had the six highest loadings of PC2. SB contributed marginally, supporting a hierarchy of influence of chemical > physical > biological. The SHI revealed mixed patterns, with high-yield zones showing higher values in only 66% of cases. However, decomposing the index provided valuable and consistent insights across both fields, that are presented jointly. SC indices ranged from 0.39–0.77–0.97 (minimum–mean–maximum), SP from 0.64–0.78–1.00, and SB from 0.08–0.19–0.35. High-yield zones had higher SC indices in 100% of cases. Spatial analysis showed that physical patterns were less limiting and more uniform across zones than SC and SB. In contrast, SB presented noisy and limiting patterns, lacking spatial structure. These findings relate to field management practices: (i) SC is routinely monitored and adjusted with lime and fertilizers; (ii) SP is accounted by controlled traffic, annual sugarcane straw input and soil preparation during replanting every 4–6 years; (iii) few actions address SB, as soil organic carbon maintenance is challenging in tropical conditions and enzymatic assessments remain uncommon. In practice, these fields appear unable to benefit from a healthy biological fraction, as they currently receive no management attention. Yield depends almost entirely on SC, which may limit resilience under adverse environmental conditions. Our results highlight that SHI assessments can guide management priorities, yet requiring careful interpretation of outcomes, since uniform or unmanaged dimensions can introduce noise and mislead decisions. Broadly, agriculture must shift toward an integrated and spatial management of SC, SP and SB to sustain the continued provision of soil functions, protecting this fragile yet vital resource for the planet.

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# Signatures of soil structural degradation: exploring stable water isotopes in soil pores

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**ABSTRACT**

Limited data exists from broad-scale surveys that assess the threat of soil structural degradation using multiple metrics, especially across multiple time-points. This was addressed by combining visual, physical and isotopic data to identify signatures of structural degradation on nine agricultural fields across three river catchments in Scotland, with sampling undertaken in September 2024, and repeated in February 2025. In each of the nine fields, three replicate samples were collected from each of: field margins, in-field locations, and areas with visible degradation to the soil surface. Intact soil cores were collected at depths of 2-7cm and 30-35cm, as well as disturbed bulk soil samples. The qualitative Visual Evaluation of Soil Structure (VESS) was combined with quantitative measurements of penetration resistance, dry bulk density, water retention characteristics and saturated hydraulic conductivity. These conventional soil physical tests were supplemented by the novel results of a rapid compaction assay and the new trial of using stable water isotopes to analyse signatures of soil pore water. For the September sampling, topsoil bulk density of in-field soils were 26.7% denser than field margins, and only 2.2% less dense than the visibly degraded locations. The February sampling showed similar results, with in-field samples 16.42% denser than the field margins, and only 0.84% less dense than visibly degraded locations. These results were also reflected in saturated hydraulic conductivity. A substantial seasonal reduction in soil structural health was found across all field locations, with bulk density for in-field and visibly degraded locations increasing by 35.7% and 37.9% respectively between September and February. Preliminary $\delta 2H$ and $\delta 18O$ data revealed a negative correlation with increasing bulk density, which may reflect different soil water storage and flow in compacted soils, and suggesting a potential alignment between stable isotope signatures and soil physical properties that could provide an indicator of soil compaction.

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# Ecological impacts of farming practices on soil quality in a Mediterranean agroecosystem

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## ABSTRACT

Sustainable agriculture hinges on plant–soil–microbe cross-talk that drives nutrient cycling, stress resilience, and biodiversity. Microbe-rich root zones, the rhizosphere and rhizosheath, are dynamic hotspots that sustain nutrient turnover and plant growth.

In a two-year field study in Caselle in Pittari (Salerno, Italy), we tested how management shapes soil biological (enzymatic activities, 16S rRNA profiles) and physico-chemical properties. We ran two trials: (1) wheat under organic amendment (SUST) versus mineral fertilization (CONV); and (2) pollinator-friendly mixes (Eco-plus, Rustico) aligned with EU CAP eco-schemes. In both trials, an unmanaged control (CTRL) with spontaneous vegetation was included. Samples were collected from bulk soil, rhizosphere (rp), and rhizosheath (rs) at pre-sowing and flowering.

An initial overall survey showed that time was the dominant driver: all enzymes peaked at flowering, indicating stronger microbial stimulation during active growth. Space also mattered: rp and rs diverged from bulk soil, reflecting strong root filtering. In trial 1, PERMANOVA detected no significant differences among CONV, SUST, and CTRL, yet NMDS revealed clear early spatio-temporal structuring. Dehydrogenase activity (DHA) was higher in rp than in bulk soil ($p < 0.05$), marking intensified plant–microbe metabolism. SUST increased labile C in bulk soil, and shifts in micronutrients paralleled changes in microbial communities. Diversity, enzyme rates, and organic matter covaried positively, but plant stage explained most separation, with biodiversity highest at flowering. In trial 2, PERMANOVA detected significant effects of plant mixes ($p < 0.05$). Rustico showed markedly higher DHA and urease than Eco-plus (both $p < 0.001$), demonstrating that plant traits strongly shape microbial responses. Sites with high enzymatic activity often exhibited lower microbial diversity, suggesting that functionality was concentrated in dominant taxa—efficiency over richness.

Overall, time is the primary driver of soil microbial activity, with functional peaks tracking crop stages and shaping soil performance. The Rustico mix stands out by boosting above-ground biodiversity while amplifying below-ground microbial processes. Thus, soil-health assessment should look beyond management labels and explicitly integrate temporal variability and distinct root-associated microenvironments. Practically, deploying diverse plant mixes, reducing mineral inputs, and continuously monitoring spatio-temporal patterns are key to safeguarding soil ecosystem services.

**Acknowledgments**

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# Arenization in the Bauru Basin, Mato Grosso do Sul, Brazil

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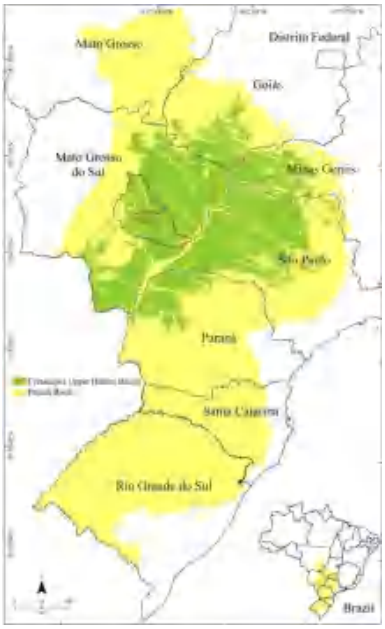
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## ABSTRACT

Arenization is a form of physical soil degradation characterized by the reworking of unconsolidated or weakly consolidated sandy deposits, resulting in the constant mobility of sediments and difficulty in vegetation establishment. Although widely studied in the southwestern region of Rio Grande do Sul, a state in the south of Brazil, where its natural origin and intensification by human activities are well documented, the phenomenon remains poorly understood in the Bauru Sedimentary Basin, especially in its western portion. In Mato Grosso do Sul, a state in the center-west of Brazil, arenization is often confused with desertification, which reinforces the need for studies that consider its genesis, dynamics, and environmental conditioning factors. This study aimed to map and analyze the evolution of sand fields in the Pardo River watershed, in Mato Grosso do Sul. Mapping was performed using the Brightness Index 2 (BI2) derived from Sentinel-2 images from the dry season of 2023. Validation was carried out by comparing the BI2 from the rainy season. Satellite images were processed using the SNAP software. The results revealed arenization foci of different dimensions and extensive degraded areas vulnerable to arenization. In the Pardo River basin, the mapped foci totaled 17,834.34 hectares, with areas ranging from less than 1 to 376.41 hectares. The arenization process occurs in different slope compartments, such as the base, slope, and interfluves, where natural vegetation has been suppressed and the soil depleted by poorly managed production processes. The physical and chemical characteristics of Quartzipsamments, such as low organic carbon content, are associated with high rates of surface exposure and weakened load-dependent structures, leading to degradation. Over time, exposed surfaces have become more vulnerable to the action of water and wind, promoting the formation and expansion of sand fields. The region's climatic conditions facilitate the advance of arenization foci, with different agents acting in distinct periods. During the rainy season, the impact of raindrops on deforested areas, low biomass production (forage), and overgrazing stand out as factors contributing to soil degradation. In the dry season, wind acts as a transporter of particles loosened by rain. This interaction between biotic factors (low plant biomass production) and abiotic factors (rocks, soils, wind, and rain) plays a crucial role in the arenization process in the Pardo River watershed. In the foci, due to the continuous supply of sand, wind acts as a dune-shaping agent throughout the year. Considering that the expansion of eucalyptus plantations occurs predominantly on sandy soils such as Quartzipsamments, in areas of degraded pastures, silviculture conceals the severity of environmental degradation. The recent land-use changes in the eastern portion of Mato Grosso do Sul–from degraded pastures to eucalyptus monocultures indicate that climate change has been largely overlooked in the state. In the southern Cerrado of Mato Grosso do Sul, where the dry season is already well defined, ongoing climate change and the global aridification process are expected to intensify aridity, prolong droughts, and aggravate environmental and socioeconomic impacts.

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# Evaluating the Impact of Stakeholder-Driven Agricultural Scenarios on Nitrogen Footprint and Virtual Nitrogen Factor using SWAT

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## ABSTRACT

**Introduction:** The Nitrogen (N) footprint (NF) is a key indicator of N issues through the involvement of stakeholders along the life cycle, and virtual N factors (VNFs) for foods are crucial to calculate food production NF. N loads from agricultural land account for a large proportion of the overall NF and are greatly influenced by production activities; however, research evaluating the impacts of agricultural activities on VNF and NF has been insufficient. The objective of this study is to calculate and compare crop yields, VNF, and NF under the current scenario and four scenarios developed based on stakeholder input. The analysis examines the impacts of these scenarios, derived from interviews with producers and policymakers, on VNFs and NFs, providing knowledge that aligns with regional needs and supports decision-making for N management.

**Method**: The target region is Mikasa City, Hokkaido, Japan, with four major crops: onion, rice, soybean, and wheat. The study period was 2000–2022. Soil and Water Assessment Tool (SWAT) 2012 Rev. 692 used to incorporate cold-region adaptation (SWAT-FSP, Mihara et al., 2024) and paddy functions (based on modified SWAT-PADDY, Tsuchiya et al., 2018). To account for parameter uncertainty in SWAT, 100 parameter sets were selected that showed a good fit between simulated and observed streamflow, sediment/TN loads, and crop yields. Annual averages of crop yields and N dynamics (precipitation N, N fixation, denitrification, volatilization, plant uptake N, river runoff N, leaching N, yield N and residual N) were calculated with these parameters. The N-Calculator method developed by Leach et al. (2012) was modified and used for VNF and NF calculation. First, VNF was calculated using statistics of N fertilizer for new input, SWAT outputs for cultivation/harvest stages and other inputs, and Shibata et al. (2014) for processing/market stages. Second, NF was calculated by multiplying each crop's VNF by its consumption N, derived from crop yield N of SWAT outputs and utilization rates by Shibata et al. (2014). Based on interviews with agricultural stakeholders in Mikasa City in 2024, four scenarios related to their farming activities of high local interest were developed (Fertilizer reduction, Organic fertilizer, Residue removal, Cover crop). Each scenario was first simulated in SWAT to estimate crop yields and N dynamics, and these outputs were then fed into the N-Calculator to calculate VNFs, and NFs.

**Results and Discussion**: The calculated crop yields, VNFs, and resulting NFs varied across the four scenarios compared to the baseline. The cover crop scenario decreased the VNFs and the corresponding NFs for all four crops without decreasing yields. Fertilizer reduction scenario decreased VNFs and NFs while maintaining onion yield. Organic fertilizer scenario showed a trade-off where both yield and VNF decreased for rice and wheat, and decreased NF. Residue removal scenario increased VNF for rice, soybean, and wheat and increased NFs, while yields remained unchanged. Notably, cover crop scenario decreased VNFs and NFs for all crops and residue removal scenario increased VNFs and NFs for all crops, therefore N flow diagrams for these two scenarios were compared. In the cover crop scenario, leaching and runoff at the cultivation stage decreased for all crops. This result was driven by two key processes represented in SWAT: (1) altered soil erosion calculations due to increase land cover (reducing runoff N), and (2) cover crop uptake of inorganic N in non-cultivation season (reducing leaching N). In the residue removal scenario, for rice, soybean, and wheat, the amount of N in removal residues exceeded the N load resulting from the in-field N losses (i.e., leaching and runoff). This occurred because residue N, which was returned to the field in the baseline scenario, was instead removed from the field, manifesting as an increase in VNF. Furthermore, because organic matter was not returned to fields, the tendency toward soil N consumption intensified for all crops, suggesting a risk of compromising long-term productivity. These analyses demonstrated that bottom-up assessment using the SWAT model not only quantifies known phenomena such as "cover crops retain soil N and suppress runoff and leaching," but also visualizes how decisions at harvest, such as “residue removal”, impact N loads (VNF and NF) across the entire food system.

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# Long-Term Land-Use Change in a Mediterranean Agroforestry System: Assessing and Restoring Soil Health in Apple Orchards of Pelion, Greece

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**ABSTRACT**

The apple cultivation in the mountainous region of Pelion (Central Greece) is a critical economic driver, providing essential socio-economic benefits and promoting rural retention. Historically, this expansion involved the conversion of forest ecosystems to orchards. This study aims to evaluate the long-term impact of this land-use change on soil health and test effective mitigation strategies for degradation. To achieve this, we are monitoring physical, chemical, and biological soil health indicators under field conditions across land uses representing successive intensities of change: intact native forest, productive, actively cultivated orchards, and abandoned orchards. The soils primarily exhibit an acidic pH (ranging from 5.02 to 7.0) and range in texture from loamy sand to clay loam. Preliminary findings show significant differences in soil organic carbon (SOC) concentration, with the forest plots containing nearly three times the concentration found in the orchards (1,5% -2%), which is expected to broadly influence overall soil function and health. To assess mitigation potential, a Randomized Complete Block Design is implemented in four active farms (blocks), comparing three management strips: 1) Local Farmer Practice (Positive Control), 2) Green Fertilization (legumes/grass cover crops), and 3) Manure Addition. An adjacent chestnut forest plot serves as land-use control. This paper will present the 1st year results of soil health scoring derived from a comprehensive suite of soil quality indicators, including; Physical Indicators (soil texture, bulk density, aggregate stability, infiltration rate, water holding capacity); Chemical Indicators (total N, SOC, C/N ratio, nutrient availability, electrical conductivity, pH); and Biological Indicators (microbial biomass C, 24h C mineralization potential, and permanganate oxidizable carbon (POX-C). The study aims to identify management options that can enhance soil health, thereby supporting the long-term sustainability and economic viability of apple cultivation in this sensitive Mediterranean mountain system.

**Key words:** soil health scoring; physical, chemical, biological soil health indicators;

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# Impact of organic mulch dose and type: A comprehensive Belgian case study

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**ABSTRACT**

Adaptive soil and water management practices are essential to mitigate the impacts of climate change, such as drought and heat stress, which are increasingly threatening Belgian agriculture and its productivity. Among these, organic mulching has been studied extensively, but rarely comprehensively. On a loamy sand soil in Belgium, three one-year field studies (2023–2025) under conservation agriculture examined the effects of organic mulch type and dose on potato (Solanum tuberosum L.) growth, soil temperature, soil water tension, nitrogen dynamics, and soil microbiome. In 2024 and 2025, the subsequent yields of summer maize (Zea mays L.) and summer wheat (Triticum aestivum L.) grown in rotation with potato were also measured, along with plant-available nitrogen. The study period covers contrasting weather conditions, with an early dry summer in 2023, a wet season in 2024, and a dry summer in 2025. Organic mulches enhanced soil water retention by reducing evaporation and improving infiltration, while also buffering soil temperature, which increased crop productivity. The type and dose of mulch stimulated microbiome communities differently and, in some instances, modified the nitrogen balance, resulting in variable effects on crop yield. Overall, grass mulch provided the most consistent benefits across different environmental conditions, still enhancing maize yield in the subsequent summer season when the initial nitrogen input was high (i.e., a higher dose). In contrast, woodchips and miscanthus negatively affected the nitrogen balance through soil nitrogen immobilization and slow mulch mineralization. This resulted in a reduced yield of potatoes under woodchips, as well as lower subsequent yields of wheat under both woodchips and miscanthus mulch. This study highlights that mulching effectiveness is influenced by the interplay between mulch characteristics and crop-specific requirements under different environmental conditions, underscoring the importance of comprehensive studies in understanding adaptive strategies.

**Keywords:** Organic mulching, crop production, nitrogen dynamics, soil water tension, soil temperature, soil microbiome

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# A Mixed-Methods Approach to Study Land Management and Soil Health in Urban Soils

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**ABSTRACT**

Urbanization is accelerating worldwide. In the Netherlands urban areas are projected to exceed 17% of its territory by 2040. Urban development often involves the construction of Technosols—man-made soils whose properties and functions are shaped by human activities. As key components of urban green infrastructure, these constructed Technosols contribute to essential ecosystem services such as flood mitigation and carbon sequestration. Most urban soils that remain unsealed occur within urban green spaces, including public parks and private gardens, where soil performance depends on both initial soil construction and subsequent management. These management decisions interact with edaphic biota, which strongly influence soil functioning. Among soil biota, earthworms play a particularly important role, especially during early-stage constructed Technosol development. As ecosystem engineers, earthworms influence urban soil functions through burrowing and casting, altering soil structure and enhancing nutrient cycling. Understanding how earthworm activity interacts with Technosol construction and management is therefore essential for supporting soil-based ecosystem services.

This research focuses on Wageningen, known as the “City of Life Sciences”, and adopts a mixed-method approach across both private and public urban green spaces. It combines (1) a survey to explore spatial variation in soil properties and management practices in private gardens, and (2) a field-plot experiment to observe dynamics in soil functions and ecosystem service delivery under realistic urban conditions.

The survey identified environmental (parent material, land cover) and anthropogenic (management intensity, gardener characteristics) factors associated with variation in soil properties. To date, 88 responses have been collected and soil samples have been taken from +30 private gardens. More than half of respondents expressed interest in soil biodiversity, highlighting the potential for citizen engagement in urban soil stewardship. The ongoing field-plot experiment simulates urban soil constructions to assess the effects of topsoil depth, vegetation type and anecic earthworms on soil ecosystem services delivery. Early observations indicate treatment-related differences in soil temperature, moisture dynamics and greenhouse-gas emissions.

By analyzing how management practices and earthworm abundance affect ES delivery—particularly regulating and supporting services— this research offers insights into how ecological and social factors co-shape urban soils. The results aim to foster greater public engagement, inform sustainable management strategies, and explore the potential of earthworm-based approaches to enhance ecosystem services in urban environments.

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# Soil health in the vineyards of North-Western Italy: a story of terroirs

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**ABSTRACT**

Despite wine is a leading agricultural product worldwide, vineyard soils are among the most eroded, often compacted, poorly structured and low in biodiversity. Conversely to many other crops, high-quality wines are generally obtained by subjecting the plants to a certain amount of stress to ensure the biosynthesis of desired secondary metabolites. This originates terroirs, i.e., specific areas where climatic, pedological and cultural conditions converge towards a particularly appreciated product. As a result of the ongoing climate change, areas of moderate stress are becoming unsuitable for high-quality wine production.

In Italy, in the Piedmont region, more than 40,000 ha are dedicated to viticulture. Here, three main grapevine black-berry varieties are cultivated (Barbera, Nebbiolo, and Dolcetto) with several local appellations (the highest being DOCG). The land is fragmented into terroirs, with Barbera vines spread over the whole region, Dolcetto grapevines localized in the south-eastern areas and Nebbiolo clustered in the northern and southernmost parts.

In the framework of the LivingSoiLL project, our research objectives were: i) to assess soil health in vineyards of the most common black-berry varieties by a soil health index (SHI) and ii) to evaluate the relationship between soil health and terroir, especially in the context of climate change.

We extrapolated topsoil data (0-30 cm) under vineyards from the regional soil database (over 2,800 points) and calculated a SHI following the Cornell assessment of soil health (CASH) taking into account some indicators of chemical fertility (N, P, CEC, pH, and available micronutrients), physical characteristics (BD, field capacity, permanent wilting point, AWC) and OM content as a proxy of biological functioning. For each indicator, cumulative distribution functions were calculated using both the soils of the whole region and specific varieties as References populations. An additive normalized SHI score was calculated for each DOCG.

The Piedmont vineyard soils are characterized by an average sand content of 30%, OM content of 15 g/kg, and BD of 1.4 kg/dm$^3$; over 70% of the soils are classified as Entisols. Most DOCG appellations are characterized by a dominant USDA soil order. Soil properties do not differ sharply among the different appellations, although some northern DOCGs have higher sand content (over 50%) and lower CEC values. One of the southernmost appellations, instead, showed low soil OM content, low AWC, and high BD, resulting in the lowest SHI values. In general, SHI scores were higher in the eastern part of the region where DOCG wines are produced from Dolcetto grapevines.

In conclusion, we highlighted the appellations that have a lower SHI and may struggle to cope with extreme events (such as droughts), while appellations with higher OM content and a better soil health are at lower risk of degradation under the ongoing climate forcing.

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# Innovating Truffle Agroforestry for Sustainable Mediterranean Landscapes: The TAIE Project

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## ABSTRACT

Truffle-based agroforestry systems are increasingly recognized for their potential to enhance soil health, biodiversity, and rural economies in Mediterranean regions. However, despite their environmental and socio-economic relevance, current practices remain fragmented, technically challenging, and highly variable in productivity. The European PRIMA project Truffle Agroforestry Innovate & Empower (TAIE) aims to address these challenges by developing and validating innovative agroforestry models tailored to truffle (Tuber spp.) and desert truffle (Terfezia spp.) cultivation. Operating across Italy, Spain, Türkiye, and Morocco, the project integrates multidisciplinary research, field experimentation, value chain analysis, and stakeholder engagement.

The TAIE project establishes five demonstration sites that reflect diverse climatic and pedological conditions, where truffle cultivation will be combined with complementary practices, such as aromatic plant intercropping, animal grazing, and beekeeping. These integrated approaches are expected to increase soil organic carbon, improve nutrient cycling, and enhance ecosystem resilience. The project also adopts advanced field monitoring tools and precision agriculture techniques to optimize irrigation, detect plant stress, and support decision-making. Soil health will be assessed through indicators aligned with the proposed EU Directive on Soil Monitoring and the "A Soil Deal for Europe" mission, including microbial activity, carbon pools, and structural stability.

The TAIE project also investigates economic barriers, socio-cultural constraints, and emerging market opportunities within truffle value chains. Certification schemes, branding strategies, and producers' willingness to adopt agroforestry practices will be analyzed to support innovative business models and strengthen rural livelihoods. A dedicated ICT platform will facilitate knowledge exchange among researchers, producers, and policy makers, while tailored learning materials and capacity-building actions will support gender-inclusive community empowerment.

As TAIE is currently at an early stage of implementation, project partners are working on the completion of baseline surveys, the harmonization of methodological protocols across demonstration sites, and the refinement of the experimental design to ensure comparability and robustness of the forthcoming results. In the medium term, the project is expected to generate measurable improvements in key sustainability indicators related to soil health, ecosystem functionality, and landscape resilience. Moreover, TAIE aims to strengthen stakeholders' readiness to adopt innovative agroforestry solutions, while increasing the visibility of Mediterranean truffle-based systems as a viable and climate-resilient land-use strategy. The project aspires to serve as a References framework for future policies, bridging scientific innovation with practical, locally adapted solutions.

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# Impact of soil amendments, irrigation regimes, and subsurface drainage on wheat yield in coastal saline soils

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**ABSTRACT**

Soil salinization is a significant challenge that declines agricultural productivity, especially in coastal regions. This study examines the impact of soil amendments, irrigation regimes, and subsurface drainage on wheat yields in coastal saline-alkali soils. The research tests various amendments, including bio-organic fertilizer, biochar, and calcium lignosulfonate, to enhance soil quality and improve crop performance. Field experiments were conducted to evaluate the effectiveness of these strategies under different irrigation regimes, including intermittent and controlled irrigation. Additionally, subsurface drainage systems were assessed for their ability to mitigate soil salinity and improve water use efficiency. Our findings highlight the synergistic impact of combining soil amendments and efficient irrigation strategies on enhancing wheat yield under a subsurface drainage system, thereby improving soil health and optimizing water management in saline-alkali soils. This research aims to provide sustainable solutions for the reclamation of saline soils and contribute to improving food security in coastal regions, thereby helping to achieve the UN Sustainable Development Goals (SDG2: Zero Hunger).

**Keywords:** Soil Amendments, Wheat Yield, Coastal Saline Soils, Irrigation Strategies, Salinity Management.

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# Decoding the Rubik's Cube of Soil Health: A Genoform-Management-Phenoform Framework for Cropland in Northeast China

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## ABSTRACT

Against the backdrop of increasingly severe global cropland soil degradation, soil health assessment has emerged as a core approach to ensuring sustainable utilization of soil resources and is crucial for mitigating degradation and restoring soil fertility. Addressing the limitation that existing soil health assessments are predominantly static evaluations lacking consideration of the matching relationship between soil inherent potential and human management activities, this study draws on social-ecological system theory to innovatively construct an integrated Genoform-Management-Phenoform (G-M-P) framework for cropland soil health assessment. Building on this foundation, the Soil Health Rubik's Cube (SHRC) diagnostic model was developed and applied to spatiotemporal dynamic analysis of Northeast China from 2000 to 2020. The study found that: (1) soil genoform endowment spatially exhibits a decreasing pattern from plains to periphery; (2) agricultural "management" intensity shows a "high in the south, low in the north" pattern and fluctuated downward from 0.26 to 0.12 during the study period; (3) based on the SHRC model, 36 G-M-P coupling types were identified, among which GH–MM–Q4 and GH–ML–Q4 are the most representative dominant types in Northeast China's croplands, accounting for 8.37% and 5.58%, respectively. The G-M-P framework proposed in this study breaks through the static limitations of traditional assessments and provides a new scientific perspective and decision support for sustainable management and policy-making of cropland soils in Northeast China and globally.

1. Introduction

Soil is the core of the Earth's critical zone, the foundation for maintaining terrestrial ecosystem functions, and the cornerstone of food security for human society ( Liu et al., 2025). However, under the dual pressures of global climate change and agricultural intensification, cropland soil degradation has become a global challenge, directly threatening the achievement of the United Nations Sustainable Development Goals (SDGs), particularly "Zero Hunger" (SDG 2) and "Life on Land" (SDG 15). Therefore, how to scientifically diagnose and effectively curb the degradation trend of cropland soils has become a major scientific issue in the fields of regional sustainable development and national food security.

Soil health assessment has evolved from the single concept of "soil fertility" to "soil quality" integrating physical, chemical, and biological attributes, and ultimately deepened to "soil health" emphasizing ecosystem functions(Doran et al., 2015;Bünemann et al., 2018; Rinot et al., 2019). The Comprehensive Assessment of Soil Health (CASH) system in the United States, the LANDMARK project in the European Union, and China's cultivated land fertility survey have established relatively mature assessment frameworks, which typically quantify the current state of soil based on minimum data sets (MDS) and multifunctionality assessments (Moebius-Clune et al., 2016; Karlen D L et al., 2019a;Garg et al., 2025; Ren et al., 2024).

Although existing studies derive comprehensive health indices through weighting and summing soil inherent properties and human management, they completely ignore the crucial matching relationship between them. Consequently, they fail to answer a series of critical questions: Are superior fertile soils activated by appropriate management? Or are they overexploited? Or underutilized? Are low-potential soils being over-developed? If the understanding of soil health remains at the level of attribute aggregation, it cannot touch upon the relational core that drives evolution. The root of this limitation lies in the failure to understand cropland as a coupled Social-Ecological System (SES). A truly scientific soil health assessment must diagnose whether the core relationship between "genoform and management" is matched.

This study takes cropland in Northeast China from 2000 to 2020 as a case study area, aiming to: 1) characterize the spatiotemporal patterns of resource baseline genoform and human utilization management; 2) analyze soil phenoform through functions and stresses; 3) identify matching patterns by coupling "Genoform-Management-Phenoform" and propose adaptive management zones.

2. Materials and Methods

**2.1 Study framework**

Cropland systems are essentially semi-natural, semi-artificial composite systems. Social-Ecological System (SES) theory provides us with a theoretical foundation for fundamentally understanding and analyzing cropland soil health (Schlüter et al., 2017) . To apply social-ecological system theory to this study, we mapped the cropland soil system of Northeast China to the core analytical units of SES theory (Fig. 1).

This study constructed the Genoform-Management-Phenoform (G-M-P) analytical framework, advancing the concepts of soil "genotype" and "phenotype" ( Droogers et al., 1997; Rossiter, 2021; McBratney A et al., 2014; McBratney Alex B et al., 2019). In the G-M-P analytical framework, Genoform corresponds to the resource system in SES, referring to the intrinsic and relatively stable attributes of soil, which are inherent variables in the system. "Management" corresponds to the combined effects of governance systems and actors in SES, referring to human interventions applied to soil, which are external variables in the system. Phenoform corresponds to the output state of resource units in SES, representing the observable comprehensive performance of soil health resulting from the interaction between Genoform and Management.

**2.2 Study area**

Northeast China primarily comprises three provinces: Heilongjiang, Jilin, and Liaoning, with geographic coordinates spanning from 118°53′E to 135°05′E longitude and 38°43′N to 53°33′N latitude (Fig. 2). The region covers a total area of approximately 790,000 km², is rich in soil types, and serves as an important agricultural production and ecological functional zone in China.

**2.3 GPI Indicator Selection and Index Construction**

Drawing on the comprehensive consideration of soil-forming factors in soil classification systems such as the Classification System for the Third National Soil Survey of China (Trial Version), the USDA Soil Taxonomy, and the World References Base for Soil Resources, this study constructed the Genoform Potential Index (GPI). Climate indicators including mean annual precipitation (PRE), mean annual potential evapotranspiration (PET), and accumulated temperature ≥10°C (GDD), terrain indicators, soil attributes including soil texture (TEX), soil depth, and coarse fragment content (CF), as well as hydrological indicators such as water table depth (WTD) were selected to assess the GPI.

**2.4 MII Indicator Selection and Index Construction**

To quantitatively assess the management intensity of human activities on cropland soils in the study area, this study integrated five key dimensions to construct the Management Intensity Index (MII) system: chemical fertilizer input, chemical regulation input, mulching material input, water resource input, and energy input (Li et al., 2025). Specifically, chemical fertilizer input included N application rate, $P_2O_5$ application rate, and $K_2O$ application rate; mulching material input included plastic film usage; water resource input included irrigation quota; and energy input included diesel consumption for agricultural machinery and agricultural electricity consumption.

**2.5 Classification of Phenoform**

Soil phenoform represents a comprehensive assessment of soil health status from two dimensions: the functions performed by the soil system and the stresses it experiences. Functions aim to quantify the actual capacity of soil to provide agroecosystem services such as production, carbon sequestration, water regulation, and biodiversity maintenance. Stresses evaluate the degree of degradation including wind erosion, water erosion, drought, and salinization. Based on the entropy weight method, the Function Index and Stress Index were quantified separately, and according to the four-quadrant method, the FRI and DRI indices were classified into four soil phenoforms: Ideal Healthy type, Degraded type, Potential Overdrawn type, and Low-efficiency Conservative type.

**2.6 SHRC Diagnostic Model**

This study constructed the Soil Health Rubik's Cube (SHRC) diagnostic model. The SHRC diagnostic model integrates three dimensions: G, M, and P (Fig. 3). Both G and M were classified into three types based on their values—low, medium, and high—while P was classified into four types. Once the three-dimensional attributes of a spatial unit are determined, it can be precisely positioned into a specific cell within the Rubik's Cube space. Each cell represents a unique combination pattern.

3. Results

**3.1 Spatial Distribution Pattern of GPI**

The spatial distribution characteristics of nine key indicators of cropland GPI in Northeast China are shown in Fig. 4(a).

Based on the comprehensive evaluation of the above indicators, the study obtained the spatial classification results of cropland soil genoform potential in Northeast China (Fig. 4b). High GPI croplands exhibited characteristics of large-scale contiguous distribution, with their extent highly consistent with the geographic location of plains. Medium GPI croplands were mainly distributed around the periphery of high-potential areas, forming an agricultural production belt transitioning from plains to mountainous and hilly regions. Low GPI croplands were primarily distributed in the hilly areas of the southwestern part of the study area.

Quantitative statistical results indicated (Fig. 4c) that Northeast China possesses superior overall cropland resource endowment, with high and medium GPI croplands accounting for more than 86% of the total area. In Heilongjiang Province, high GPI croplands accounted for 61.78%, while low GPI croplands represented only 3.58%. Jilin Province was dominated by medium genoform potential croplands, accounting for 55.08%. Liaoning Province had a relatively high proportion of low genoform potential croplands, reaching 40.78%.

**3.2 Spatiotemporal Evolution Characteristics of MII**

Although MII fluctuated over time, its spatial distribution pattern remained relatively stable, with high-intensity areas concentrated in the central and southern plains, while the northern and eastern regions consistently remained low-intensity zones. The study analyzed the changes in the proportional structure of MII levels across different regions during the study period (Fig.5(b)). Quantitative analysis of regional average MII also confirmed the temporal variations across different provinces (Fig.5(c)). The overall average MII in Northeast China declined from 0.26 in 2000 to its lowest point of 0.08 in 2010, then rose to 0.19 in 2015, and finally decreased to 0.12 in 2020.

**3.3 Evolution of Soil Phenoform: Function, Stress, and Phenoform**

Soil functions showed overall improvement (Fig. 6). Spatially, functions exhibited a general pattern of "high in the north, low in the south", which was largely consistent with the distribution of genoform potential.

Ecological stresses intensified significantly, and risk types underwent shifts (Fig. 7). Wind erosion and drought risks declined, but water erosion intensity and salinization degree increased markedly. Spatially, water erosion in eastern Liaoning Province, salinization along the coast, and drought in the west formed compound stresses; western Jilin Province faced dual pressures from wind erosion and salinization.

During the study period, the area proportion of "Ideal Healthy" type (high function, low stress) cropland significantly declined from 38% to 27%. Meanwhile, two unsustainable phenoform types expanded dramatically: the area proportion of "Potential Overdrawn" type (high function, high stress) increased more than threefold, surging from 4.32% to 18.58%; the area proportion of "Degraded" type (low function, high stress) also rose significantly from 15% to 24%.

**3.4 Diagnosis of Genoform-Management-Phenoform (G-M-P) Coupling Patterns**

Based on the Soil Health Rubik's Cube (SHRC) model, spatiotemporal dynamic diagnosis was conducted on 36 types of "Genoform-Management-Phenoform" (G-M-P) coupling patterns in Northeast China from 2000 to 2020, revealing the complex evolution and significant spatial differentiation of regional cropland health patterns (Fig.9). GH–MM–Q4 and GH–ML–Q4 are the most representative dominant types in Northeast China's croplands, accounting for 8.37% and 5.58%, respectively, widely distributed in the Sanjiang and Songnen Plains and their northeastern forest-agriculture transition zones, characterized by the stable conversion of high potential into Q4 phenoform under relatively moderate input intensity. GM–MH–Q2 and GH–MH–Q2 are the fastest-expanding types over the past two decades, accounting for 6.17% and 3.48%, respectively, primarily concentrated along the Liaoning coast, central mining and industrial corridor, and western Jilin plains, presenting an imbalanced state of "high input but limited function and intensified stress"; the third category is the overdrawn types of GH–MM–Q1 and GM–MH–Q1 , accounting for 3.82% and 2.42%, respectively, characterized by the coexistence of high function and high stress, typically occurring in scenarios of mountain development and peri-urban intensive utilization, driven by processes such as water erosion or salinization.

4 Discussion

**4.1 From Attribute Integration to Relational Diagnosis: Methodological Innovation**

Existing studies often integrate various attributes into a single index, which tends to misidentify high yield but high-risk units as healthy. In contrast, this study constructed a diagnostic Rubik's Cube by integrating soil genoform potential (GPI), human management intensity (MII), and phenoform (P), enabling the identification of high yield but high-risk phenomena. For example, in sloping croplands and coastal salinization-sensitive areas, high-intensity inputs sustain relatively high production but simultaneously significantly elevate water erosion and salinization risks, causing units to shift from "Ideal Healthy" type to "Potential Overdrawn" type. Therefore, this study elucidates when, where, and why phenoform differences occur.

**4.2 Zoning Management Strategies and Policy Implications Based on G-M-P**

Optimization and enhancement zones such as GH–MM–Q4 and GH–ML–Q4 are widely distributed in the central-northern Heilongjiang plains, serving as the core food security zone of Northeast China. Through conservation tillage, precision fertilization, organic amendments, and other technologies, soil carbon stocks and biodiversity can be enhanced while maintaining high yields, creating model sustainable agricultural areas. Restoration and rehabilitation zones such as GM–MH–Q2 and GH–MH–Q2 are concentrated in coastal Liaoning, central regions, and western Jilin. Measures including fertilizer and pesticide reduction, cropping structure adjustment, fallow rotation, and irrigation-drainage system restoration should be implemented to break the "high input-high stress" vicious cycle, reduce stress, and restore functions. Early warning and monitoring zones such as GH–MH–Q1 and GM–MH–Q1 are distributed in mountain reclamation areas and peri-urban intensive use zones. Monitoring and early warning systems should be established, development intensity controlled, soil and water conservation strengthened, and ecological restoration on sensitive areas guided to prevent sharp deterioration of soil health. Potential activation zones such as GM–ML–Q3 are scattered in northwestern Heilongjiang and other marginal areas, serving as strategic reserve zones. Under strict ecological risk assessment, production potential should be activated in an orderly manner through scientific planning and moderate inputs, avoiding the pattern of development followed by remediation.

**4.3 Limitations and Prospects**

(1) Lack of dynamic tracking of genoform evolution. This study treated GPI as a relatively stable inherent attribute, but long-term human management activities can actually cause gradual changes in soil genoform. For example, sustained organic amendments can improve soil texture and depth, while excessive reclamation leads to soil erosion and organic matter loss, thereby altering the soil's inherent potential. Future research should quantify the long-term modification effects of different management practices on soil genoform maps.

(2) The causal mechanisms between management and phenoform still require further investigation. The current study identified the spatial patterns of G-M-P coupling types, but the causal pathways of "which management combinations under which genoform backgrounds lead to which phenoform transitions" have not been fully revealed.

(3) Insufficient scale conversion and refined diagnostic capability. This study achieved soil health diagnosis at the regional scale, but its application at the field scale still requires optimization.

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Fig. 1. Application of social ecosystem system theory in soil systems



Fig. 2. Overview Map of the Study Area.



Fig. 3 Genoform–Management–Phenoform framework



Fig. 4. Spatial distribution and grade composition of GPI in the study area. (a) Spatial distribution of GPI evaluation indicators. (b) Classification results of GPI spatial distribution. (c) Proportion of GPI grades in Northeast China overall and by province



Fig. 5. Spatial distribution and grade composition of cropland soil management intensity in the study area. (a) Classification results of MII spatial distribution. (b) Temporal changes in average MII by province. (c) Temporal changes in the proportion of MII grades in Northeast China overall and by province.



Fig. 6. Soil Functions



Fig. 7. Soil Stress



Fig. 8. Diagnosis and Analysis of Phenoform



Fig. 9. Diagnosis and Analysis of GMP

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# Effects of Land-use Variation on Soil Infiltration Capacity and Preferential Flow in Typical Low Hilly Area

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**ABSTRACT**

Large-scale vegetation rehabilitation introduced in low-hilly areas to decrease soil erosion disasters is an important method. Consequently, it is worth paying attention to the influence of soil infiltration capacity that results from the changing of land use types. To date, few studies have been conducted on the mechanism of how changes in land usage influence soil permeability or preferential flow development. The dye tracer method and indoor experiments were adopted in the present study to quantitatively analyze the differences in physicochemical properties of soils, their impact on preferential flow development and soil permeability in paddy fields, dry land, and forest land. It was found that forests and dry lands have a greater soil penetration capacity than paddy fields, with the stable infiltration rates at 0–20 cm and 20–40 cm depths being greater by 43.52–73.15% and 129.41–529.41%, respectively. The preferential flow development differs depending on land usage patterns, forest land has the less value the stained area ratio (20%) and matrix flow depth(2.15 cm) and the greatest value of the preferential flow ratio(84.93%), length index(10.11), stained variation coefficient(0.91) and peak number(19.40), compared with dry land and paddy fields. The result of variance analysis shows that soil bulk density and moisture content have inhibitory effects on preferential flow development and infiltration capacity and that greater porosity and organic matter content promote infiltration and preferential flow. These findings are important for understanding the hydrological mechanisms taking place in soils and are of assistance in agricultural land management.

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# Changes in salinity and vegetation growth under different land use types during the reclamation in coastal saline soil

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**ABSTRACT**

The ecological construction in coastal saline-alkali areas urgently needs to be explored in terms of water-salt regulation management and functional irrigation. In this paper, the extremely severe saline soil in the eastern coastal area of the North China Plain was selected for vegetation rehabilitation by drip irrigation. Through two-year field experiments, the spatial and temporal soil salinity-water dynamics of three land use types (LUTS) under two irrigation strategies (IIS) were systematically studied. The results revealed: (1) The soils in the understory grassland and shrub land root zones remained stable for desalination, with the average ECe decreasing to 0.69 dS/m and 0.71 dS/m under autumn irrigation at surface, and 0.66 dS/m and 0.85 dS/m under winter irrigation. And a slight salt accumulation occurred in the bare land in stage IV. (2) The soil surface moisture increased, and the bulk density decreased significantly with drip irrigation. The final moisture of understory grassland and shrub land was 3.85 and 2.97 times that of the bare land layer at 0-10 cm, 2.55 and 1.97 times at 10-20 cm, and 1.61 times and 1.47 times at 20-40 cm, respectively. (3) Due to quick salt rinsing, Salix matsudana and Hibiscus maintained a high survival rate, and the germination of understory vegetation further increased the vegetation coverage. Meanwhile perennial understory herbs gradually became the dominant species, which positively effects on the maintenance of soil low-salt environment. (4) There were significant differences in SWC and ECe between autumn and winter irrigation treatment during stage I and stage II, indicating that irrigation strategies only impact on soil water-salt movement in the early stage. While there was no significant difference between understory grassland and shrub land, indicating that the research about the effects of vegetation cover type on water-salt transport should take a longer time scale.

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# Soil health and carbon sequestration dynamics in sandy soil within the Low Carbon Brazilian Beef protocol

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**ABSTRACT**

Brazil has approximately 100 million hectares of pastures with medium to low vigor, a situation that is even more critical in sandy soils due to their chemical, physical, and biological fragility. To address this problem, the Brazilian government issued a decree aiming to restore around 40 million hectares of degraded pasture by 2023, and the introduction of integrated systems has emerged as a viable technology to achieve this goal. In 2019, a research initiative was launched by Embrapa at Fazenda Trijunção, located in western Bahia, Brazil, to study the management of a sandy soil, plant, and animal components through the implementation of the Low carbon beef (LCBB) protocol, under integrated crop-livestock production system. For the soil component, samples were collected at depths of 0–10 cm, 10–20 cm, and 20–40 cm to measure the soil health (specifically in the 0–10 cm layer) (Mendes et al., 2024) and carbon sequestration (CS). The study evaluated the LCBB protocol against a LCBB control, that represents the conventional system or extensive pasture (low input), and the natural Cerrado (Cer) as a baseline. Carbon sequestration was found to be higher in the LCBB (13.55 and 11.77 Mg $ha^{-1}$) compared to the LCBB control (10.89 and 9.48 Mg $ha^{-1}$) and to the Cerrado (8.64 and 9.61 Mg $ha^{-1}$) in the 0–10 cm soil layer for 2019 and 2023, respectively. In the 10–20 cm soil layer, no significant differences were observed among the three systems. However, in the 20-40 cm soil layer, the Cerrado exhibited greater CS than the LCBB and LCBB control systems, but only in 2023, with no significant differences observed between the latter two. No significant differences were observed between 2019 and 2023 within each system. Results from 2019 indicated that both, LCBB and LCBB control, showed a critical soil health condition, with scores falling between the “getting sick” and “unhealthy” classes, respectively. This condition reflected the history of extensive use and low organic matter inputs typical of extensive pastures in Brazil. In the 2023 sampling, the recovery trend was consolidated in LCBB, classifying the soil as “healthy,” while the LCBB control remained in the “getting sick” condition, with no significant changes since 2019. These results indicate a progressive gain in organic carbon and an improvement in nutrient storage in the LCBB area. The higher forage and meat production observed in the LCBB (data not presented) further supports the potential of the LCBB protocol as effective solutions for restoring degraded pastures.

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Trijunção Farm and Low Carbon Plataform

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# Improving Soil Health in An Irrigated Arid Agroecosystem

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## ABSTRACT

Farming systems in the southwestern United States are facing intense challenges due to recurrent droughts and land degradation. Agricultural producers are actively seeking methods to enhance soil health and improve soil resiliency against drought. A long-term soil health study was initiated at the Leyendecker Plant Science Research Center in Las Cruces, New Mexico, USA, to investigate the impact of management practices on soil health indicators in a corn silage (*Zea mays* L.) cropping system. Tillage methods tested on the plots every year were conventional, strip tillage, and no-tillage. Cover crop treatments imposed on the plots every year include no cover crop (NC); single species cover crop (SC), [triticale (*x Triticosecale* Wittmack), and multiple species cover crops (MC), [a mixture of triticale, barley (*Hordeum vulgare*), Austrian winter pea (*Pisum sativum* L.), and daikon radish (*Raphanus sativus*)]. Soil amendment treatments consisted of a compost-biochar blend, applied only once at two rates (0 and 33.6 Mg/ha). The biochar made from lodgepole pine (*Pinus contorta* Douglas ex Loudon) was 10% of the blend. The treatment combinations were replicated four times, and the plots were maintained under the same treatments. Multiple physical, chemical, and biological soil measurements were assessed. After four years, significant main treatment effects were observed for many of the soil indicators measured. Two-way and three-way interactions were mainly not significant for the indicators. The compost-biochar amendment resulted in a 16% increase in soil organic matter (SOM). It increased several plant nutrients in the soil, including Olsen phosphorus by 76%, potassium by 9%, zinc by 56%, iron by 12%, and copper by 7%. The amendment application also resulted in a slight but significant reduction in pH. The SC cover crop treatment had the highest total microbial (TM), total bacterial (TB), total fungal (TF), and arbuscular mycorrhizae fungi (AMF) biomasses compared to MC and NC. Compared to the NC treatment, the SC increased TM by 30%, TB by 30%, TF by 75% and AMF by 66%. Furthermore, the cover crop treatment (both SC and MC) increased the soil aggregation by an average of 11% and soil water infiltration by an average of 33% compared to the NC treatment. No-tillage treatment had 7.5% more SOM than the strip tillage treatment, but it was not statistically different from the conventional tillage. The impacts of reduced tillage were not shown for many of the indicator measurements, probably due to the longer time it takes for its benefits to become apparent. This study demonstrates that using cover crops and organic amendments could provide quicker benefits for soil health improvements in irrigated arid agroecosystems.

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# Dynamic of soil organic carbon and phosphorus for different technological options in the Peruvian Amazon

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**ABSTRACT**

The Peruvian Amazon covers 60% of Peru's territory and consists of tropical forests with very high biodiversity. The predominant soils are Ultisols, which are acidic, infertile, and low in organic matter and phosphorus (P) with a high percentage of aluminum saturation. Currently, 10 million hectares of this region have been deforested by migratory slash-and-burn agriculture and. Soil organic carbon (SOC) and available P are the best indicators of soil productivity and fertility and monitoring them over time will allow for the diagnosis of the recovery or degradation of Amazonian soils. The objective was to evaluate the dynamics of SOC and P over five years in 15 technological soil use systems (SUS) along the Tarapoto-Yurimaguas highway in the Peruvian . The study was conducted in two locations in Yurimaguas (Loreto) and Tarapoto (San Martin), on Ultisols soils. The SUS evaluated in the lower Amazon were primary and secondary forest, multi-layer SAF (*Cedrelinga cateniformis* and *Centrosema macrocarpum*) with 10% and 4% clay, Brazil nut (*Bertholletia excelsa*) with coffee (*Coffea arabica*), oil palm (*Elaeis guineensis*) with kudzu (*Pueraria phaseoloides*), palmito (*Bactris gasipaes*), pijuayo (*Bactris gasipaes*) with kudzu, improved grass (*Brachiaria brizantha*) with centrosema and degraded (native grass with a predominance of torourco (*Axonopus compressus*)). In the high forest, cocoa (*Theobroma cacao* L.) was evaluated with secondary forest shade, cocoa with planted shade trees, cocoa without shade with centrosema cover, improved coffee (*Coffea arabica* L. var. Caturra) and traditional coffee, both under shade. SOC, bulk density and available P were measured at two depths (0-15 and 15-30 cm). The evaluations were carried out during the lowest and highest rainfall periods, with an annual average of 2200 mm. SOC shows fluctuating dynamics, with accumulation favored by dry seasons and decomposition favored by rainy periods. In general, the surface layers of the SUS contain higher SOC, fluctuating from 0.35 to 1.94% in the SUS located in the Amazonian plain, which tend to have lower COS content than the SUS located in the high jungle, which fluctuated between 0.74 and 3.92%. Of the SAFs, cocoa grown under secondary forest shade has the highest SOC content (1.68-3.92%), while perennial crops such as oil palm, pijuayo, and others exhibit the lowest contents (0.57-1.69%). Available P was very low in the lowland forest SUS, except for the fertilized pijuayo, and the upland forest SAFs had higher levels due to better soils and fertilization. SOC showed a cyclical accumulation trend favored by the dry season and greater mineralization during wet seasons. The surface horizon had higher SOC and P contents, which were higher in the SUS of the Upper Forest. Among the forest-cocoa SAFs, SOC and P were higher than in systems with perennial crops. SOC was proven to be a robust indicator that depends on climate and soil management.

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# Effects of straw returning method and irrigation lower limit on soil water and salt regulation and crop physiological characteristics in saline-alkali land of the Yellow River Delta

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**ABSTRACT**

Optimizing saline-alkali soil management in the Yellow River Delta requires understanding the interaction between irrigation regimes and straw return methods under water scarcity. A maize-wheat rotation system was employed with two irrigation lower limits (W1: -30 kPa, W2: -60 kPa) and four straw return methods (RS: in-situ return; RM: manure return; RB: biochar returning; RG: pellet returning) on soil parameters (pH, EC, organic matter, available nutrients) and crop physiological indicators (antioxidant enzymes, photosynthesis, growth traits, and yield). The RB treatment with W2 irrigation is projected to significantly improve soil conditions by reducing EC and increasing organic matter. RB and RM treatments are anticipated to enhance antioxidant enzyme activities while reducing MDA content and boosting photosynthetic rate. The moderate water deficit with RB/RM treatments is expected to achieve higher water use efficiency while maintaining or improving yield by 5-10%. The findings will demonstrate that moderate water deficit combined with biochar or manure returning constitutes an effective model for sustainable agricultural production in saline-alkali soils.

**Keywords:** Straw return; Irrigation lower limit; Saline-alkali soil; Water-salt regulation; Physiological characteristics

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# Effects of regenerative organic agriculture on soil quality and plant biochemistry

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**ABSTRACT**

The intensification of agriculture has often led to the degradation of soil, which is a critical non-renewable resource. This study suggests that regenerative organic practices can reverse this trend, enhancing soil ecosystem functions and improving water and nutrients biogeochemical cycles. Our research, conducted at the European Regenerative Organic Center (EROC), will specifically investigate: (1) the temporal dynamics of soil quality indicators – including organic matter pools, nutrient content, microbial community structure and activity, hydrological and physical properties – under a prescribed regime of cover crops, organic amendments, and minimal disturbance; and (2) the subsequent translocation of soil-derived benefits into the plant system, measured as shifts in nutrient content and secondary metabolite profiles.

Preliminary baseline data and the experimental framework for tracking changes in key soil health indicators: soil organic matter (SOM) dynamics, microbial biomass and activity, and water-stable aggregates. Crucially, this study moves beyond soil metrics to explicitly trace the soil-plant continuum. We are analyzing how shifts in soil microbial community structure and nutrient cycling – particularly the mobilization of nitrogen, phosphorus, and micronutrients – influence the biosynthesis of plant secondary metabolites and the nutrient density in harvested crops.

Achieved and expected results include a quantifiable increase in soil organic carbon and a shift in microbial biodiversity towards fungal-dominated communities, providing a mechanistic understanding of the soil-plant nexus. We anticipate demonstrating that these ecological intensification strategies not only support yields but fundamentally enhance the nutritional value of crops. The broader impact of this work is to provide robust, scientific evidence to catalyze a circular bioeconomy, where agricultural value is derived from enhancing natural capital rather than depleting it, directly supporting European objectives for sustainable food systems.

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# Post-Agrogenic Ecosystem Recovery in the Smolensk Lakeland: a Comprehensive Study in Western Russia

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**ABSTRACT**

The dynamics of the land cover of the territory within the modern boundaries of the Smolensk Lakeland National Park (Russia). A comprehensive study in the Smolensk Lakeland National Park analyzed natural recovery of ecosystems on abandoned farmlands: 3 chronoseries (Pine, Spruce, and Mixed coniferous-broadleaf reforestation) across 7 stages. The methodology included 173 vegetation plots, 80 soil pits, >2,500 soil, 447 macrofauna and 196 metagenome samples.

Successions of the 3 series develop according to a common scheme, but have specific features. Due to similar environmental conditions and nearly identical recovery responses, the Pine and Spruce series were grouped into one technobiogeome by M.A. Glazovskaya (units with a similar recovery response after plowing ceases. In a 1:150,000 scale, the map of technobiogeomes is based on indicator properties that define each recovery stage:

Stage 0: plowing area.

Stage 1 (fallow meadows; up to 30 years of reforestation): A continuous Oi and Oe layer forms. Macrofauna diversity is low ("arable" type). The soil microbiome begins to shift. Soil macrofauna diversity increases ("meadow" type).

Stage 2 (forests; up to 30 years): A fragmented Oe layer appears. In P and S series, total carbon (SOC) and nitrogen (Ntot) levels recovered in the Oi layer, soil pH recovered.

Stage 3 (60-70 years): A Oa layer forms. In the Oi layer of the M series, SOC and Ntot are restored. Forest herbs begin to replace meadow species. In soil, "sorest" macrofauna appeared.

Stage 4 (up to 80 years): The Oa layer gains mass. The former plow layer (Ap) degrades significantly. Epigeic macrofauna diversity is fully restored.

Stage 5 (up to 110 years): The A(p) horizon transforms into a native-like A layer. The soil saprophagous complex recovers. Tree species ratio normalizes; herbaceous weedy plants disappeared.

Stage 6 (>110 years): In herb and shrub layers, composition of plant life-forms is restored. The soil microbiome is fully recovered. Windfall soil complexes and large decomposing logs appear. Signs of the old plow layer remain visible in the soil profile.

According to the cluster analysis, P, S and M forest ecosystems recover in 30, 70 and 80 years, respectively. According to ordination regression based approach, ecosystem recovery rates decrease with time. The P and S series ecosystems recover in 75 – 105 years, faster than the M series (117 – 127).

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# Impact of Intensive Vegetable Production on the Properties of Andisol

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**ABSTRACT**

The conversion of forests to agricultural land use is widespread across many parts of the tropics and is considered a major cause of soil degradation (Asio et al., 2024). On Leyte Island in central Philippines, large areas of volcanic mountain slopes with young volcanic soils (Andisols) have been cleared and converted into intensive vegetable farms. The cool and wet climate (Af in Koeppen climate classification) due to its high elevation (700-900m asl) and the excellent physical properties of the Andisols favor the intensive cultivation of high-value vegetables such as cabbage (*Brassica oleracea*), beans (*Phaseolus sp.*), squash (*Cucurbita maxima*), bell pepper (*Capsicum annuum*), Chinese pechay (*Brassica rapa*), eggplant (*Solanum melongina*), and tomatoes (*Solanum lycopersicum*). Farmers practice heavy application of chicken manure, combined with chemical fertilizers, with or without lime. The objective of the study was to evaluate the impact of intensive vegetable cultivation on the morpho-physical, chemical, and biological properties of the Andisol soil formed from andesitic pyroclastics (Jahn and Asio, 2006). Using the adjacent area approach (space-for-time substitution approach), farms that had been cultivated intensively for varying durations ranging from over 10 to over 60 years were evaluated and compared with the adjacent natural forest. The five (5) farms selected were intensively cultivated for >10, >20, >30, >40, and >60 years, respectively. Soil profiles representing the forest and the vegetable farms were described and sampled, and composite surface samples from the 0-20 and 20-40 cm soil depths were collected for laboratory analysis of physical, chemical, and biological properties.

Results revealed that the soils in the forest and intensively cultivated farms have comparable horizons in their profiles, suggesting similar genesis. The soils are all young volcanic soils characterized by a cambic B horizon (Bw). Prolonged cultivation increased bulk density due to soil compaction from tillage and field operations, thereby decreasing porosity. Conversely, the forest showed lower bulk density and higher porosity values. The forest exhibited the highest water-holding capacity due to better soil aggregation and higher organic matter content. However, long-term intensive cultivation, particularly in sites with over 60 years of cultivation, reduced the water-holding capacity due to soil compaction and structural alterations. Agricultural practices slightly modified the natural soil textures, which were primarily driven by erosion, sedimentation, translocation, and weathering. Soil pH changed slightly due to prolonged cultivation. However, pH fluctuations occur across different cultivation periods, with deeper soils exhibiting slightly higher pH values. Soil organic matter decreased with prolonged cultivation, particularly in surface layers, while total nitrogen levels remained relatively stable. Available phosphorus levels increased with long-term cultivation, attributed to fertilizer use and organic material application. Exchangeable potassium levels remained higher in cultivated farms than in the forest, emphasizing the impact of agricultural practices on nutrient management. Exchangeable calcium and magnesium concentrations varied among farms, influenced by management practices and fertilizer application. Long-term cultivation led to a decrease in soil exchangeable calcium levels, highlighting the impact of intensive farming on soil nutrient dynamics and fertility. Comparable $CO_2$ evolution rates were observed between vegetable farms and the forest site. Still, farms with longer cultivation durations exhibited higher rates due to greater organic matter input from crop residues and compost.

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# Scale-dependent mechanisms of grazing-induced soil carbon sequestration: Mediated by soil nitrogen quantity vs. heterogeneity in grasslands

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## ABSTRACT

Herbivore grazing is a key driver of soil organic carbon (SOC) sequestration in grassland ecosystems. Plant diversity responses and their linkages to soil limiting resources play a critical role in mediating the impacts of grazing on SOC dynamics. Soil nitrogen (N) is widely recognized as the primary limiting resource in grassland ecosystems, however, the mechanisms by which grazing regulate SOC stocks by shaping the relationships between soil N availability (in terms of quantity and spatial heterogeneity) and plant diversity across varying spatial scales remain poorly understood. Here, we conducted a 9-year controlled sheep grazing experiment in the Horqin sandy grassland of northeastern China to explore how grazing impacts SOC stocks at the large (25 m×25 m) and small (5 m×5 m) spatial scales. We found that grazing significantly increased SOC stocks at both large and small scales. At the large scale, grazing not only directly increased SOC stocks but also promoted SOC sequestration via enhancing the positive correlations between the heterogeneity of soil N availability and plant α-diversity. At the small scale, in addition to directly increasing SOC stocks, grazing facilitated SOC sequestration through boosting the relationships between the quantity of soil N availability and plant α-diversity. Furthermore, grazing had no effect on SOC stocks by altering plant β-diversity, irrespective of spatial scale. Therefore, our findings indicate that the scale-dependent mechanism underlying grazing-induced promotion of SOC stocks operates through regulating the associations of the quantity and heterogeneity of soil limiting resources and plant α-diversity in grasslands. These findings further highlight the significance of grazing-mediated synergistic linkages among "soil resource heterogeneity-plant diversity-ecosystem function" for maintaining grassland ecological processes. We therefore recommended long-term moderate sheep grazing as an effective grassland management practice for enhancing grassland soil C sequestration.

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# Soil quality variation and its driving factors in rubber plantations of tropical China

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## ABSTRACT

Understanding the key factors that determine soil quality is essential for the recent and rapid expansion of rubber plantations in the tropics. Tropical China is an ideal experimental area because its rubber plantations are geographically dispersed and belong to different climatic zones. Soil quality in this study was comprehensively evaluated using a soil quality index (SQI) based on 28 soil physical, chemical and biological properties. And the factors driving variation in the SQI of rubber plantations were analyzed utilizing the redundancy analysis and a structural equation model. The results indicated that no age effect of the plantation on soil quality was observed in the same rotation period, whereas the SQI of rubber plantations was found to be relatively low after long-term cultivation. There was an apparent discrepancy in the spatial distribution of the SQI of rubber plantations. And the SQI demonstrated a declining trend with increasing soil depth, with the SQI of the surface soil layer (0-10 cm) exhibiting a significantly higher value than that of deeper soils. Soil condition was found to be predominant in the SQI variation of rubber plantations, particularly the seven soil properties including saturated water capacity, easily oxidizable organic carbon, ammonium nitrogen, available phosphorus, total potassium, manganese, and zinc. The direct effects of geographical location, vegetation cover, and climatic variables on rubber plantation SQI variation were relatively weak, while they indirectly affected the SQI variations by influencing the soil condition. The SQI results are expected to provide a quantitative foundation for enhancing soil quality in rubber plantations in the tropics.

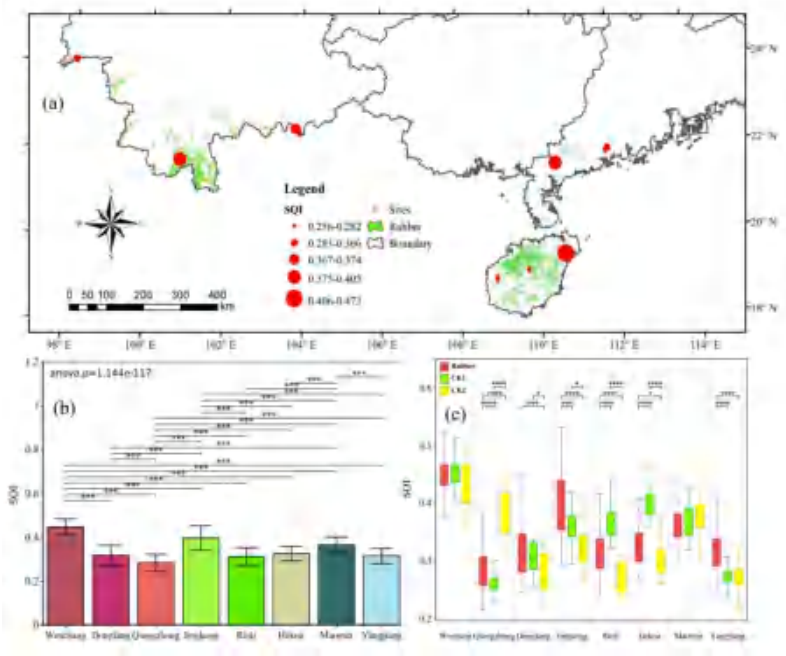



Fig.1. Soil quality index (SQI) values under rubber plantations on tropical China: (a) spatial distribution, (b) variation among eight planting regions, (c) difference between rubber plantations and References plots (CK1 and CK2 are two tropical vegetation).

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# Distribution of Available Phosphorus in the Soils of Belgrade Across Urban Development Zones

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## ABSTRACT

Phosphorus is an important indicator for understanding the characteristics of urban soils, as its concentrations reflect both the intensity and the duration of anthropogenic influence in cities. In urban environments, phosphorus levels are shaped by multiple factors, including the degree of urbanization, historical and current land use, atmospheric deposition, inputs from traffic and pets, management of green areas, fertilizer use, and organic waste accumulation. Soil available (labile) phosphorus (SAP) is particularly important because it directly reflects the portion of phosphorus that is exchangeable, mobile, and accessible to plants and humans. Monitoring SAP makes it possible to reconstruct past land-use practices, detect disturbed or anthropogenic horizons, and assess the magnitude of human impact on the urban pedosystem. Excessive SAP concentrations may also migrate through the unsaturated zone and affect groundwater quality, while imbalances in the root zone can limit nutrient uptake and influence vegetation health. Therefore, SAP represents a valuable chemical marker for interpreting the properties and functioning of urban soils. This study examines the variability of SAP in Belgrade's soils in relation to the degree of urbanization, represented by four spatial zones (central, suburban, external, and rural). SAP was measured in 126 composite samples from topsoil (0–10 cm) and subsoil (10–40 cm) using the Egner–Riehm Al method (Knežević and Košanin, 2011). Mean SAP concentrations (mg/100g) in topsoil followed a clear urban-rural gradient: central (65.44) > suburban (38.58) > external (13.25) > rural (7.25). Subsoil showed the same pattern, ranging from 65.28 in the central zone to 3.88 in the rural zone. SAP values displayed a wide range in urban zones (e.g., 0.52–558.74 mg/100g in central topsoil), while rural soils showed considerably narrower variability. Overall, extremely high SAP concentrations were recorded in some locations, which considerably exceeds the upper threshold of the very high SAP class (>20 mg/100 g) by more than an order of magnitude. The results indicate a pronounced increase of available phosphorus toward the city centre, forming a distinct urban "hotspot". These exceptionally high SAP concentrations, particularly in the central and suburban zones, likely reflect long-term cumulative anthropogenic inputs typical of large metropolitan areas, such as the continuous population growth, development of the transport network and increase in vehicles, higher presence of pets, among others. This pattern emphasizes the need to account for urbanization processes in soil planning and management and their influence on regional phosphorus cycling and phosphorus availability for urban vegetation.

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# Rate of decomposition of litter fall and nutrients recycling in three soil use systems in the Peruvian Amazon

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**ABSTRACT**

Within the overall functioning of forests and other soil use systems (SUS) in the humid tropics, litter plays a very important role in energy flows and nutrient recycling and is often considered the largest flow of nutrients between vegetation and the soil surface. Decomposition and nutrient input are a fundamental process for the growth of trees, shrubs, and other species in the great biodiversity of plants found in the forest in the humid tropics. The study was conducted in three contrasting and representative SUS in the humid tropics of the Peruvian Amazon in Yurimaguas (Department of Loreto), including primary forest (PF), pijuayo (*Bactris gasipaes*) with kudzu (*Pueraria phaseoloides*) (PK), and improved grass (*Brachiaria brizantha*) with centrosema (*Centrosema macrocarpum*) (IG). The decomposition rate of leaf litter and the contribution of carbon (C), nitrogen (N), phosphorus (P), and potassium (K) was evaluated over a year using nylon mesh decomposition bags with a 5 mm opening, which were placed in very good contact with the soil surface. Six bags were collected monthly from each SUS to evaluate the remaining biomass and released nutrients. Analysis of variance (ANOVA) was used, where the SUS and months were considered as the main effects. During the evaluation year, rainfall was 2,200 mm per year, with periods of higher rainfall between September and March. When characterizing the chemical composition of leaf litter, the PF system had the highest % of C, lignin, and lignin/N ratio, the PK had the highest % of N and K and the lowest %P and lignin/N ratio, while the IG had the lowest % N and lignin and the highest % P. The PF soil is extremely acidic with 60% aluminum saturation, while the PK and IG soils have a moderate pH and lower acidity. The PK and IG systems showed similar decomposition rates, higher than that of the PF, and the remaining biomass at the end of the year was 8.32% and 6.58%, respectively. Likewise, N release rates were higher in the PK and IG systems, increasing during the rainy season, as these systems maintain leguminous cover crops that recycle N and decompose more quickly. The contribution of leguminous leaf litter in the recycling process improves the quality of humus with the formation of humic and fulvic acids that also determines the quality of the clay-humic complex and maintains better soil physical and chemical properties.

At the end of the evaluation, the following order of nutrient release from leaf litter was observed in the three systems evaluated: potassium > phosphorus > nitrogen = carbon. The dynamics of decomposition are linked, first and foremost, to the composition of plant material in terms of lignin concentration and the lignin/nitrogen ratio, followed by climatic conditions and the coverage (architecture) of the system, and finally the intense activity of the microorganisms and macrofauna associated with soil quality and health.

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# Tillage Intensity as a Driver of Soil Bacterial Composition and Functional Potential

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## ABSTRACT

Soil microbial communities play a critical role in nutrient cycling and agroecosystem resilience, yet their responses to long-term tillage practices in semiarid environments remain poorly understood. This study evaluated the effects of 20 years of conventional tillage (CT), minimum tillage (MT), and no-tillage (NT) on soil bacterial communities, integrating physicochemical analyses with high-resolution 16S rRNA amplicon sequencing to characterize shifts in microbial diversity and taxonomic composition. Soil samples were collected from a long-term tillage experiment established in Policoro, Southern Italy, where durum wheat (*Triticum durum*) and faba bean (*Vicia faba*) have been grown under a biennial rotation for over 20 years. Composite soil samples (0–30 cm depth) were taken from replicated plots.

Although major chemical properties, such as pH, organic matter, total nitrogen, and carbonates showed no significant differences among treatments, MT and NT soils improved the availability of key micronutrients relative to CT. Copy numbers of the functional microbial genes involved in denitrification (*nirK*, *nirS*), iron reduction (*gltA*), and sulfate reduction (*dsrAB*) were significantly higher under NT and MT than CT, indicating stimulated anaerobic microbial processes in reduced-tillage systems.

Sequencing revealed a pronounced compositional restructuring of bacterial communities across treatments. NT and MT soils were enriched in copiotrophic phyla such as Actinobacteria and Firmicutes, consistent with improved nutrient retention and reduced physical disturbance. Conversely, CT soils were dominated by oligotrophic phyla adapted to nutrient-poor and disturbed environments. Venn analysis highlighted distinct microbial signatures for each management system, with MT harboring the greatest number of unique genera, followed by NT and CT, demonstrating that long-term tillage intensity strongly filters community membership. Beta-diversity analyses (PCoA, PCA, PERMANOVA) demonstrated clear community separation among tillage regimes, confirming robust shifts in bacterial assemblages, although alpha diversity (Faith's PD) showed no significant differences among treatments.

Overall, long-term NT and MT practices reshape soil bacterial communities toward functionally enriched, nutrient-responsive taxa and promote key microbial processes, underscoring the ecological advantages of conservation tillage for sustainable soil management in semiarid agroecosystems.

**Acknowledgments**

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# Soil health and ecosystem services across land uses and biogeographical regions in Europe

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## ABSTRACT

Soil knowledge across Europe varies considerably depending on biogeographical region and land use. In this context, there is a notable lack of information regarding soil ecosystem service interactions, particularly in Boreal, Alpine, and Atlantic regions under wetland and semi-natural land uses. On the other hand, urban, forest, and mining soils show high uncertainty due to their pronounced heterogeneity and contamination levels. This study evaluates key physico-chemical parameters related to different ecosystem services across 25 experimental sites distributed over five biogeographical regions (Alpine, Atlantic, Boreal, Continental, and Mediterranean) and seven land use types (urban, industrial, agricultural, forest, mining, semi-natural, and wetland). The effects of region and land use on a range of soil quality and health indicators including physical and chemical properties at 0–20 cm depth were assessed. Results show that organic soils in the Boreal region have significantly higher total organic carbon (TOC), particulate organic carbon (POC), $NH4^+$, and exchangeable Na compared to mineral soils in other regions. Among mineral soils, higher inorganic carbon, exchangeable Ca, cation exchange capacity (CEC), and pH were found in the Mediterranean region. At the regional level, industrial soils from Alpine region showed higher levels of bioavailable Al and Fe than agricultural and wetland land uses. In the Atlantic region, semi-natural soils exhibited higher soil water at field capacity (SWC), soil water at wilting point (SWW), TOC, POC, $NH4^+$, and bioavailable Al compared to agricultural soils. In the Boreal region, mining soils showed higher TOC and POC than agricultural soils. In the Continental region, forest soils contained more TOC and POC than soils under urban, agricultural, mining, and semi-natural uses. Finally, in the Mediterranean region, semi-natural soils displayed higher SWC, SWC, TOC, POC, exchangeable Ca, and CEC compared to industrial soils. These findings highlight the elevated organic matter content of organic soils, and the surprisingly high fertility indicators in Mediterranean soils, which are typically considered low fertility. In general, Semi-natural and forest uses tend to enhance soil organic matter and structure.

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# Decades of Data: Evaluating soil dynamics under contrasting tillage systems in Fuchsenbigl, Austria, since 1988

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**ABSTRACT**

Publishing soil data is pivotal for advancing soil research and informing policy decisions, as it provides harmonized information and facilitates access to relevant data (Panagos et al., 2022). Adhering to FAIR principles enhances the reusability and interoperability of data, contributing to a better understanding of soil and agricultural systems (Lachmuth et al., 2025). Long-term agricultural field experiments (LTEs) are essential for comprehending sustainable farming systems, offering invaluable insights into management practices and their impact on soil processes, productivity and environmental interactions, which unfold slowly, necessitating decades to observe measurable changes (Johnston & Poulton, 2018). The Austrian Agency for Health and Food Safety (AGES) has therefore established several LTEs in major agricultural production areas in Austria to provide data and deepen understanding of the impact of various agricultural management practices on soils such as different tillage systems. This study describes data obtained from a tillage LTE established in 1988, and still running today, containing data on soil chemical, physical and biological parameters, primary production (yields), plant nutrients and management data. The tillage LTE, which is conventionally managed, is located in Fuchsenbigl, Lower Austria, in the main production area of the Marchfeld (north-eastern lowlands and hills). Three different treatments are applied: minimum tillage (5-8 cm), reduced tillage (15 cm) and conventional tillage (25-30 cm). The soil parameters are available at various soil depths to a maximum of 100 cm. This study offers invaluable insights and advances our understanding of the agroecological implications of contrasting tillage systems.

**Keywords:** long-term field experiment, soil data, agricultural management practices, eLTER, agroecology

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# Soil Health in U.S. Northern Great Plains Agriculture: A Comprehensive Review and Meta-Analysis

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**ABSTRACT**

Selecting agricultural practices that strengthen the resilience of production systems is essential for improving agricultural sustainability. This is especially true in the U.S. Northern Great Plains (NGP), where extreme weather events are common, and the adoption of soil health practices can provide substantial agronomic and environmental benefits. The objectives of this research were (i) to identify and rank the most frequently studied soil health practices and indicators in the NGP, and (ii) to quantify the effects of the five leading practices on soil organic carbon (SOC). A comprehensive search was conducted in Web of Science, Scopus, and ProQuest to identify all published articles, theses, and dissertations using the following search terms: [("soil health" or "soil quality") and ("Northern Great Plains" or "North Dakota" or "South Dakota" or "Montana" or "Wyoming" or "Minnesota" or "Nebraska" or "Alberta" or "Saskatchewan" or "Manitoba")]. The search returned 897 publications, which were then screened to remove duplicates. From the complete database, a total of 160 studies were selected using the following criteria: (i) conducted in cropland or rangeland systems, (ii) located within the NGP, and (iii) evaluated at least one soil health practice falling within one of the following broader categories: cover crops, crop rotation, crop sequence, crop-livestock integration, grazing, non-agricultural ecosystems (e.g., grassland, prairie), reduced tillage, organic amendments, residue management, and water management. Across all studies, the five most measured soil health indicators were, in order: soil organic carbon (SOC), bulk density, soil inorganic nitrogen, total nitrogen, and pH. The five most frequently studied practices were crop sequence, cover crops, no-till, crop rotation, and grazing. For the meta-analysis, we focused on SOC and these five leading soil health practices. To ensure equivalent comparisons across studies, the dataset was stratified by soil depth (topsoil [0–15 cm] and subsoil [15–30 cm]) and study duration (short-term [≤ 7 years] and long-term [> 7 years]). The SOC effect size was expressed as the ratio of SOC under the soil health practice relative to its corresponding control. In the topsoil, all practices increased SOC across both study durations, with the strongest effects observed under long-term crop rotation, cover crops, and grazing. In contrast, short-term studies showed greater SOC gains from crop sequence, no-till, and grazing. In the subsoil, cover crops did not significantly affect SOC at either study duration, whereas no-till consistently increased SOC in the long term. Overall, none of the practices increased subsoil SOC in the short term. These findings indicate that increasing SOC and improving the resilience of production systems in the NGP is achievable when soil health practices are implemented, and that these benefits can be strengthened when multiple practices are integrated.

# The nonlinear response effect of arable land quality on arable land fragmentation in mountain areas

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## ABSTRACT

Clarifying the nonlinear impact of arable land fragmentation (ALF) on arable land quality (ALQ) has important significance for the protection and sustainable utilization of arable land resources. Taking the mountain areas in eastern Liaoning Province, China as the research object, this study used the LESA (Land Evaluation and Site Assessment) model and the landscape pattern indices to construct an evaluation system for ALQ and ALF. The piecewise linear regression model and the conditional inference trees were used to analyze the nonlinear impact of the ALF indices on ALQ and the thresholds. The results show that ALF shows a two-stage impact on ALQ, i.e., strong inhibition and weak promotion. The critical thresholds of the impact of the ALF indices, including the arable land fragmentation index (ALF), shape fragmentation index (SFI), distribution fragmentation index (DFI), and area fragmentation index (AFI) on ALQ are 0.155, 0.341, 0.07, and 0.089, respectively. In terms of the fractal dimensions of ALF, the impact of mean patch size (MPS) and aggregation index (AI) on ALQ is characterized by strong suppression and weak promotion, with thresholds of 5.842 ha2 and 96.618%, respectively. Edge density (ED) and area-weighted mean shape index (AWMSI) exhibit strong inhibition and weak promotion impacts on the ALQ, with critical thresholds of 2.28 and 0.155 m/ha, respectively. The comprehensive evaluation of the multiple indices of ALF shows that when AWMSI ≤ 1.977, MPS > 6.593 hm2, and ED ≤ 172.719, the optimal ALQ in the mountain area appears. The research results provide support for the protection and management of arable land.

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# Initial soil carbon status governs soil C stock changes, while pore characteristics improve after conversion of arable land to semi-natural grassland

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## ABSTRACT

The conversion of arable land to grassland is widely recognized as an effective measure to mitigate climate change and reduce soil degradation. However, the extent to which this conversion influences soil properties remains poorly understood, particularly in relation to initial soil organic carbon (SOC) content and the subsequent rate of change in soil characteristics.

Soil samples were collected from the Askov long-term straw incorporation and cover cropping experiment, initiated in 1981, terminated in spring 2020, and subsequently converted to semi-natural grassland. The site is located in southern Jutland, Denmark (55°28′N, 09°06′E) on sandy loam in a cool temperate climate. The experiment followed a two-factorial split-plot design with three replicates: main plots varied in straw incorporation rate (SR), and subplots included cover crop (CC) treatments with or without ryegrass. Spring barley (*Hordeum vulgare* L.) was grown from 1981 to 2019, with straw incorporated at 0, 4, 8, or 12 Mg ha$^{-1}$ yr$^{-1}$. In 2020, a grass mixture was undersown in barley; after harvest, no fertilizer was applied, and grass biomass was cut annually in August and left on the plots.

Loose soil was sampled from 0–20 cm in December 2019 (pre-conversion) and October 2023 (3.5 years post-conversion). Intact 100 cm$^3$ cores were taken from 6–10 cm in spring 2020 and autumn 2023. SOC was determined by dry combustion. Intact cores were analyzed for water retention at matric potentials of −1, −3, −10, −30, and −100 kPa, air permeability at −3, −10, and −30 kPa, and gas diffusivity at −10 kPa. Soil porosity was estimated from bulk density and predicted particle density (Schjønning et al., 2017).

SOC content was significantly influenced by SR and CC both before and after conversion. Bulk density decreased from 1.53 to 1.43 g cm$^{-3}$ and was only affected by SR prior to conversion. SOC stock change from 2020 to 2023 showed a near-significant SR effect (P = 0.07), with the greatest increase under straw removal and the largest decrease under 12 Mg straw ha$^{-1}$ yr$^{-1}$. SOC stock change correlated strongly with initial SOC. Before conversion, total porosity and plant-available water capacity were significantly affected by SR and CC, mainly through differences in 3–10 µm and 10–30 µm pores. After conversion, treatment effects disappeared, but total porosity increased from 0.415 to 0.455 m$^3$ m$^{-3}$, primarily due to expansion of >30 µm pores, especially >300 µm. Relative gas diffusivity, air permeability, and pore organization improved significantly, while tortuosity decreased. These findings indicate that conversion to grassland affected SOC dynamics depending on initial SOC status but markedly improved soil structural properties, overriding prior management effects.

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# SoilBio Reveals the Power of Forage Grasses to Improve Biological Functioning, Soil Health and Long-Term Soybean Yield in Maranhão, Brazil

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## ABSTRACT

Healthy soils are fundamental to the sustainability of tropical grain production systems, particularly in regions characterized by high temperatures, increasing dry spells, and rapid turnover of soil organic matter. Under these conditions, management practices that strengthen biological functioning are essential for maintaining soil resilience and stable crop yields. Embrapa's Soil Bioanalysis Technology (SoilBio) provides an integrated approach to soil health assessment, combining routine chemical analyses with the quantification of key enzymatic activities—arylsulfatase (ARYL) and β-glucosidase (BETA)—which reflect essential nutrient-cycling processes. These indicators can provide insights into how cover crops influence soil functioning over time. SoilBio was applied to a field experiment established in 2021 in Balsas, Maranhão State, a major soybean-producing area within the MATOPIBA region of Brazil. The objective was to assess how forage grasses and other cover crops affect soil health and cumulative soybean yield across four growing seasons. Cover crops used in succession to soybean or in consortium with off-season maize included four forage species [*Urochloa brizantha* cv. Marandu, *U. ruziziensis*, *Megathyrsus maximus* var. Zuri, *M. maximus* var. Tamani] and a legume (*Crotalaria spectabilis*). Controls were soybean/fallow, soybean/maize, and soybean/millet. Treatments were arranged in strips with three repetitions. Soil samples from the 0–10 cm layer were collected in March 2024 and April 2025 for SoilBio analyses, and cumulative yield was calculated from four growing seasons. Yield was related to cycling, storage, and nutrient supply function scores. Forage grass–based treatments significantly improved soil biological functioning, with ARYL and BETA activities increasing by 67% and 85%, respectively, compared with fallow. These changes were accompanied by a 14% increase in soil organic matter and a 13% rise in cumulative soybean yield. Soybean productivity was strongly correlated with the SoilBio cycling function score ($r^2 = 0.56$), while no significant relationship was observed with storage or supply scores, indicating that nutrient cycling processes are the primary drivers of yield responses under the evaluated tropical conditions. The results highlight the importance of forage grasses as effective cover crops to promote soil health in soybean production areas of Maranhão. Additionally, the study demonstrates the robustness of SoilBio as a practical and sensitive tool to support the identification of sustainable soil management practices, reinforcing its value for guiding management decisions in tropical agricultural landscapes.

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# Nitrogen dynamics, Soil Health, and Yield Responses under Long-Term Fertilizer and Manure Management in SAT of Central India

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## ABSTRACT

Improving and maintaining soil quality in order to increase and sustain agricultural output is vital to India's food and nutritional security. To increase nitrogen use efficiency and reduce losses in Vertisols, a better understanding of nitrogen dynamics is necessary. The continuous use of organic manures in conjunction with fertilizers may increase mineralization and immobilization of plant nutrients, altering their levels in various organic and inorganic forms in soil (Umesh et al. 2014). When fertilizer N is applied preplant, it is concentrated at the beginning of the season, with soil N becoming the dominant N pool once the fertilizer N supply is depleted or immobilized (Bufogle et al. 1997). In the long-term fertilizer experiment being studied across the country, farmyard manure (FYM) incorporation has resulted in increased N mineralization potential in different cropping systems.

The existing system of fertilizer application is based on the nutrient requirement of the individual crop ignoring the carry over effect of the manures or fertilizer application to the succeeding crop to a great extent. Further, application of inorganic fertilizers even in balanced amount doesn't sustain the soil productivity. The indiscriminate use of chemical fertilizers is likely to cause environmental hazards, necessitating the need to develop a sustainable production system. In this context, integrated use of fertilizer with organics like farmyard manure, vermicompost and green manure assumes a greater importance as these organics improve the soil productivity and sustainability and brings down the mounting pressure on inorganic fertilizer substantially. Long-term fertilizer experiments (LTFE) have generated enormous and valuable information which could be used for sustainability of high input intensive agriculture. Therefore, the present investigation was carried out to study the long-term effect of nutrient management on various N fractions and their relative contribution to yield of sorghum and wheat.

The experiment was laid out in randomized block design with the following treatments for sorghum and wheat: (CK); absolute control (plots did not receive NPK fertilizers and FYM), (CF1); 50% NPK, (CF2 + OM); 75% NPK (recommended dose of fertilizer) + FYM, (CF3); 100% NPK, (CF3+S); 100% NPK + sulphur @ 37.5 kg $ha^{-1}$, (OM); FYM @ 10 t $ha^{-1}$ (each for sorghum and wheat) annually 20 t $ha^{-1}$ and (CF3+RM); 100% NPK + residue management. Each treatment was replicated four times. The required amount of well-decomposed FYM was applied on an oven-dry basis 5-7 days before sowing the sorghum and wheat crops. The recommended dose of fertilizer for sorghum it was 100: 50: 40 kg N, $P_2O_5$ and $K_2O$ $ha^{-1}$ and for wheat it was 120: 60: 60 kg N, $P_2O_5$ and $K_2O$ (annually for both the crops it is 220: 110: 100 kg N, $P_2O_5$ and $K_2O$ $ha^{-1}$) applied through urea, single super phosphate and muriate of potash in all treatments with two splits of nitrogen at the time of sowing and the remaining at 30 days after sowing for sorghum and 21 days after sowing for wheat. The full dose of P and K was applied at the time of sowing.

The representative moist soil samples were collected through a soil auger from surface layers (0–15 cm) from each plot during wheat and arranged as a composite sample as per standard protocol for laboratory analysis of soil. Organic carbon was determined following the procedure as described by Walkley and Black (1934). Available N was determined by alkaline-$KMnO_4$ method (Subbiah and Asija 1956). Available P was determined by extracting soil with 0.5 *M* $NaHCO_3$ as described by Olsen *et al.* (1954). Available K was determined by neutral normal ammonium acetate method (Hanway and Heidel 1952). Total N in soil samples was determined by digestion of soil samples with sulphuric acid at a temperature between 360 and 410 $^0$C in presence of $K_2SO_4$: $CuSO_4$ mixture followed by distillation. The ammonia liberated in the distillate was absorbed in boric acid and titrated against 0.005 *N* $H_2SO_4$ (Bremner 1965a). Inorganic (ammonium + nitrate)–N was determined by 2 *M* KCl extract as per the method given by Bremner (1965b).

**Mineral N dynamics in Sorghum-Wheat cropping sequence**

The results of the present experiment indicated that, the mineral N among various treatments ranged between 25.6 to 55.3 mg $kg^{-1}$ (Figure 1). The mineral N was increased significantly with the increasing levels of NPK alone or in combination with FYM. The application of FYM @10 tones $ha^{-1}$ each for sorghum and wheat (20 tones annually) and 75% NPK along with FYM were equally effective in improving the status of mineral N in soil. However, the magnitude of increase in mineral N was noted in the order of 50% NPK, 100% NPK and 150% NPK which could be attributed to the increasing order of fertilizer application. The increase in the mineral N content of soil with the

combined application of manures and fertilizers might be due to higher accumulation of organic matter and its subsequent decomposition and mineralization which contributed to accumulating higher amount of N over suboptimal treatments (Basumatary and Talukdar 1998). The contribution of inorganic N to total N was increased with the fertilizer N application to both the crops increased from 75 to 100% NPK. The higher mineral N contribution, however measured in plots receiving balanced fertilization alone or along with FYM. The higher mineral N content in soil was noticed during sorghum compared to wheat. The greater mineral N levels in soil during sorghum can be linked to favourable soil conditions, as contrasted to extremely low temperatures during wheat season, which may impact mineralization.

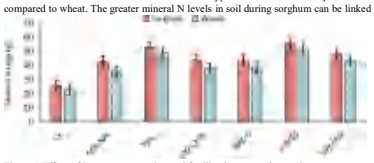


Figure 1 Effect of long term manuring and fertilization to sorghum-wheat sequence on mineral N during sorghum and wheat cropping in Vertisol

**SOC and Soil Properties**

The SOC content increased with various fertilizer and manure treatments over the initial status (4.6 g $kg^{-1}$) after continuous cropping for 37 years in all the treatments except 50% NPK. The increase in SOC content under integrated use of fertilizers and organic manure treatments might have been due to direct incorporation of organic matter, better root growth and more plant residues addition. Continuous use of balanced fertilizer over a period of time increased the available N, P, K and S status gradually under all the treatments than the control, and the maximum increase was observed with 75% NPK + FYM. The favourable soil conditions provided by FYM addition might have helped in mineralization of additional soil N leading to build-up of higher available N (Santhy *et al.* 1998). Almost all treatments enhanced available P status in soil, with the exception of the control, 50% NPK, and FYM alone treatment (FYM 10), which showed very little improvement. The higher available K observed under the NPK + FYM treatment is attributed to the direct addition of K through FYM, improved cation exchange capacity, reduced K fixation, reduced NPK level (50% NPK) and control treatments receive limited K inputs and show greater K depletion. The various fertilizer treatments greatly increased the soil's S status. This increase in available S was due to the application of single superphosphate (SSP) as a source of P, which contains a significant amount of S. The application of 75% NPK caused significant improvement in soil physical (bulk density, hydraulic conductivity and MWD) and biological properties (dehydrogenase, MBC, urease and phosphatase) indicating overall improvement in soil condition as evidenced by soil quality index (SQI). Based on the SQI, organic carbon, dehydrogenase activity, and hydraulic conductivity were identified as sensitive indicators that can change rapidly in response to management interventions. The sensitivity of organic carbon, dehydrogenase activity, and hydraulic conductivity suggests that these variables can serve as early and reliable indicators of soil quality changes resulting from management interventions. Manna et al. (1996) observed that an increase in dehydrogenase following the application of FYM might be attributed to an increase in microbial growth with the addition of carbon substrate. The only organic treatments found to be effective were those that increased dehydrogenase activity significantly. This can be ascribed to the fact that, as the primary source of carbon, organic materials and nutrients give energy for soil microbes and increase the number of pores, which are considered crucial in the soil-water-plant relationship, as well as maintaining excellent soil structure in conjunction with dehydrogenase.

**N uptake and N use efficiency**

The N uptake increases with N fertilization levels with balanced use of P and K fertilizer and showed further increase in presence of FYM. In general, the N uptake response was improved when 75% NPK was supplemented with FYM. The magnitude of N use efficiency was slightly increased with increase in levels of N, however, it was improved with balanced fertilization, further improvement was noticed with organic manure. Wanjari et al. 2022 reported that nutrient use efficiencies (NUE) in general of applied N, P and K in majority of crops gradually improved with addition of each nutrient. The efficiency further improved with INM, i.e. NPK+FYM across LTFE

sites. However, NUE had drastically reduced due to imbalanced use of fertilizers (Jadhao et al. 2019).

**Yield and sustainable Yield Index**

The various fertilizer treatments recorded significant increase in the grain yield of sorghum and wheat (Figure 1) over control (after 37th cropping cycle). The productivity, which further improved with the combined application of organic and inorganic fertilizers (75% NPK+ FYM). The increase in yield of sorghum and wheat was recorded to the tune of 39.5 per cent and 49.2 per cent over sole chemical fertilizer (100% NPK) highlighting importance of organic manure in availability of nutrients and thereby maintaining soil fertility. Furthermore, the integrated supply of nutrients was found beneficial for higher grain yield of sorghum and wheat which can be attributed to the addition of organics through FYM and supply of balanced nutrition in addition to micronutrients. Application of 75% RDF + FYM was significantly superior over 100% NPK indicating possibility of compensating 25% chemical fertilizer through FYM. Yaduvanshi *et al.* (2013) reported that yield of rice could be sustained with 50% recommended dose of NPK with green manure (GM) or FYM indicating the usefulness of organic manure in replacing chemical fertilizer.

The SYI of system productivity (sorghum and wheat) was greater in 75% NPK + FYM. The application of FYM alone resulted in a lower SYI of system productivity when compared to the application of inorganic fertilizers alone or in combination with FYM, which could be related to sole application of FYM's could not sustain sorghum and wheat yields. The system's sustainability can be realized by an integrated approach to nutrient management. As a result, applying 75% NPK + FYM @ 5 t $ha^{-1}$ could be an alternative for achieving long-term greater yields in the sorghum-wheat cropping system. Singh (2010) reported that the increase in SYI following the application of 150% NPK indicates that the levels of nutrients applied at 100% NPK are insufficient to realize the potential crop yields. Of course, an increase in SYI as a result of FYM treatment over and above NPK suggests that, in addition to nutrient supply, soil physical and biological factors are also crucial components in maintaining crop yield.

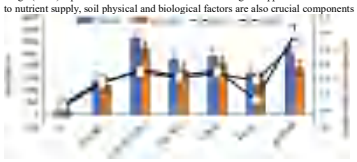


Figure 1 Effect of long-term manuring and fertilization to sorghum-wheat sequence on yield and sustainable yield index of sorghum and wheat

**Correlation among mineral N fraction and yield**

The inorganic N fraction was found to be significantly and positively correlated with all the forms of N indicating dynamic equilibrium between different fractions. This implies that, the dominant N fractions are the potential contributor towards plant available N (Kaur and Singh 2014). As a results, the contribution of the dominant N fractions are generally more in achieving sustainable yield. The yield of sorghum and wheat was significantly and positively correlated with the different N fractions. The higher correlation coefficient was recorded among yield and $NO_3$-N followed by $NH_4$-N indicating dominance of nitrate-N fraction for obtaining higher yield of sorghum and wheat.

Based on 37 years of long-term fertilizer experiment on the sorghum-wheat sequence, integrated nutrient management is critical for maintaining soil fertility, improving nitrogen dynamics, and yield sustainability in Vertisols. The combination of organic manure (FYM) with chemical fertilizers, particularly the 75% NPK + FYM treatment, significantly increased mineral N availability, soil organic carbon, and soil nutritional status when compared to fertilizer use alone. These enhancements resulted in improved N absorption and nitrogen-use efficiency, showing that long-term FYM integration improves N dynamics and mineralization. Importantly, the efficacy of 75% NPK + FYM was comparable to 100% NPK alone, demonstrating the potential to save 25% chemical fertilizer without sacrificing soil health or crop sustainability. Furthermore, long-term crop performance trends show that integrated nutrient supply consistently produces the highest grain yields of sorghum and wheat. The substantial positive association between mineral N fractions and yield highlights the relevance of increased nitrogen availability in promoting long-term productivity. Overall, the study demonstrates that combining organics and inorganic fertilizers not only sustains soil health over decades, but also enhance environmental sustainability by reducing fertilizer dependence. Thus, the 75% NPK + FYM strategy emerges as a feasible, resource-efficient choice for maintaining yield and soil quality in intensive sorghum-wheat production systems.

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# Biochar amendment mitigates negative effects of controlled irrigation on paddy soil structure: insights from micro-pore network analysis

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## ABSTRACT

With increasing rice production demands and water scarcity, developing water-saving irrigation techniques for paddy fields is a global priority. The impact of these techniques on soil structure remains unclear, especially under varying water-carbon conditions. From 2022-2023, field experiments examined four biochar rates and two irrigation methods (controlled irrigation (CI) and flooding irrigation (FI)), resulting in five treatments: CK (0t/ha+CI), CA (60t/ha+CI), CB (30t/ha+CI), CC (10t/ha+CI), and FK (0t/ha+FI). Compared to FK, CK decreased mean weight diameter (19.73-25.54%), soil organic matter (4.64-9.79%), total nitrogen (2.68-10.59%), dissolved organic carbon (1.90-9.48%), water content at saturation (0.23-15.83%) and permanent wilting point (3.69-7.87%), while it increased unstable aggregates index (6.29-15.11%) and fractal dimension (1.59-1.88%). Biochar treatments (CA, CB, CC) mitigated CK's adverse effects on soil aggregate stability, total nitrogen, and water retention capacity and significantly improved these indicators. CA increased porosity across various effective pore diameters, while CB and CC primarily increased the proportion of porosity for diameters >250μm. Simulation results indicated that compared to CK (3.879μm²), the intrinsic permeability (K) of soil under CA, CB, and CC treatments increased by 106.69%, 77.77%, and 3.31%, respectively, while FK showed a contrasting decrease of 3.58%. K correlated well with >250μm porosity and connected porosity representing microstructure, with correlation coefficients of 0.96 and 0.94. Overall, biochar improved chemical properties and micropore structure (porosity for diameters >250μm, connected porosity) of soil aggregates under CI, enhancing macroaggregate functions such as soil stability and hydraulic properties.

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# Biochar application influenced soil quality in China's Loess Plateau

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## ABSTRACT

While the role of biochar in improving problem soils has gained recognition, its specific impact on loessial soil remains insufficiently studied, particularly due to a lack of long-term field monitoring data. This study aims to develop a Soil Quality Index (SQI) for biochar-amended loessial soil based on 25 soil property indicators. A field experiment was conducted from 2017 to 2024, comprising six treatments with biochar (derived from apple tree branches) applied at rates of 0%, 1%, 2.5%, 4%, 5.5%, and 7%. Following the establishment of a Minimum Data Set (MDS), a comprehensive SQI will be calculated by integrating the selected indicators using multivariate statistics-specifically Principal Component Analysis-combined with non-linear scoring functions. The objectives of this research are to (1) assess the effects of biochar application on soil quality through multiple evaluation methods, and (2) develop predictive models for soil quality based on key soil factors under biochar amendment. Data analysis is currently underway.

***Keywords:*** Biochar; Minimum Data Set; Soil Quality Index; Predictive models; Loess Plateau

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# Effects of protection time and stationary state on the fractal dimensions characteristics of the sandy soil in Hunshandake Sandy Land

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## ABSTRACT

The soil is a kind of porous medium made from different size and shape of solid particles and gap with a certain form. There was the irregularity and the randomness characteristics in the physical property indexes of the soil. Because of the complexity of the soil composition, restricted by research methods and technical means, it was difficult to describe the nature and forms of the soil quantitatively. After the 1990, with the cross and integration of the subjects, fractal geometry entered the fields of soil science, and was used to describe soil properties such as soil particle surface area, soil particle weight and particle size distribution. Not only the soil particle morphology could be reflected by fractal dimension, but the soil structure could be describe by the change of the soil particles fractal dimension. Fractal theory has become an important method for quantitative description of soil character. The obvious results could be obtained by use of fractal theory to explain the phenomenon which was irregular, instable and complex. The application of fractal theory in soil science provides a new methodology and approach for studying the fine structure of the soil. HunShanDaKe sand is located in the Inner Mongolia autonomous region, is the nearest sand to Beijing. Since 1960s, HunShanDaKe sand area expands significantly, desertification land area of the early 1960s and the mid 1970s was 192000 $hm^2$ and 265900 $hm^2$. After the 1990s, the average annual desertification expansion rate increased. Under the action of strong cold air in the spring and autumn, sand could fly over the yanshan mountains to Beijing , formed the dust storm, threat the ecological environment of the region.

Two series of plots was built. One was in the sand of 16 years governance, 10 years governance and natural restoration of grassland; another was in the sands of 16 years governance, but with different succeed stage of flowing sand, semi-fixed and fixed sand. Three 80 cm soil profile was dig in each plot, and soil sample of 0 ~ 5 cm 5 ~ 10 cm, 10 ~ 20 cm, 20 ~ 30 cm, 30 ~ 40 cm, 40 ~ 60 cm was took to experiment room. According to the classification standard of soil particles, division level of soil particles was Gravel particles: Fine gravel (2 ~ 1 mm); sand: coarse sand (1-0.25 mm), fine grains of sand(0.25 ~ 0.05 mm); Powder: coarse powder (0.05 ~ 0.01 mm), fine powder (0.01 ~ 0.005 mm); Clay: thick clay(0.005 ~ 0.002 mm), clay( < 0.002 mm). The grain composition of the soil sample was measured by use of soil screening method and the hydrometer method.

Through the field investigation and room analysis, by using of fractal model created by Peiling Yang, the granulometric distribution and the fractal dimensions of the sand soil under different protection time and different stationary state in Hunshandake Sandy Land was studied. It was showed that: (1) The soil belongs to sand soil texture classification according to Chinese standard. The sand fraction of soil particles was mainly distributed in 1 ~ 0.05 mm diameter section, content was 85.97% ~ 96.59%. Coarse sand (1 ~ 0.25 mm) content was 14.8% ~ 52.9%, fine sand (0.25 ~ 0.05 mm) content was 14.10% ~ 69.96%. Powder and clay content was less than 5%, 0.01 ~ 0.005 mm of fine powder and 0.005 ~ 0.002 mm thick clay content was the minimum; (2) Coarse sand and clay grain contents were the main factors to decide fractal dimension. The more coarse sand grain content in the soil, the smaller the fractal dimension. The more clay content in the soil, the bigger the fractal dimension. No matter what kinds of recovery time and fixed stage, fractal dimension of soil particle was relevant to mechanical composition of soil particles. Giving the same recovery time and different fixed state, the fractal dimension were significantly negative relevant to the content of coarse sand (1 ~ 0.25 mm) in the soil particles, negative relevant to the contents of fine gravel (2 ~ 1 mm) and fine sand (0.25 ~ 0.05), significantly positive relevant to the content of clay (< 0.002) and thick clay (0.002 ~ 0.005) , positive relevant to the content of coarse powder (0.05 ~ 0.01) and fine powder (0.01 ~ 0.005). Giving the different recovery time, the fractal dimension were significantly negative relevant to the content of coarse sand(1 ~ 0.25 mm) , negative relevant to the content of fine gravel (2 ~ 1 mm) and fine sand (0.25 ~ 0.05 mm), significantly positive relevant to the content of coarse powder (0.05 ~ 0.01 mm), fine powder (0.01 ~ 0.005 mm) and clay (< 0.002 mm) , positive relevant to the content of thick clay (0.002 ~ 0.005 mm); (3) Sand soil fractal dimension changed with the soil layer, the deeper the soil layer, the smaller the fractal dimension; (4) With the protection time increased, sandy silt and clay content increased and sand content decreased, the fractal dimension would increased. The fractal dimension of the soil was bigger under higher vegetation coverage than that under lower vegetation coverage, the fractal dimension of the soil was greater under fixed sandy land than that under unfixed sandy land. The results would provide the theory basis for the sandy land protection.

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# Long-Term No-Tillage Effects on Plant Residue Decomposition and Soil Organic Carbon Formation and Accumulation Patterns in a Japanese Andosol

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## ABSTRACT

Long-term no-tillage (NT) can enhance soil carbon stocks in Japanese Andosols and therefore has the potential to contribute to climate change mitigation in temperate humid environment. However, uncertainties still remain on the long-term NT effects on residue decomposition and C accumulation patterns and variability in distribution into distinct SOC fractions and their implication for soil carbon stabilization. We conducted a one-year field incubation experiment using $^{13}C$ labelled plant residue applied to undisturbed soils from long-term NT and disturbed soils from conventional tillage (CT) plot, taken from the Centre for International Field Research, Ibaraki University, Japan. The objective of the study was to quantify the effects of long-term NT versus CT and mode of residue C input (surface vs mixing) on residue decomposition and vertical migration of residue-derived C into distinct SOC fractions in Japanese Andosol. $^{13}C$-labelled ryegrass residue (C:N = 25.8, 7 atom% $^{13}C$) was applied at 2 Mg C $ha^{-1}$ (1.8 g C $kg^{-1}$) under three treatments: surface application on NT (NTSA), mixing with CT (CTMIX) and surface application on CT (CTSA, positive control), with soil-only controls (NT and CT) and incubated under field conditions (n = 4). Residue-derived C (RDC) in SOC was assessed over time by $^{13}C$ analysis at four depths (0–2.5, 2.5–5, 5–10, 10–15cm). Residue-derived $CO_2$ emissions, microbial biomass C (MBC), and dissolved organic C (DOC) were also measured. Soil organic matter (SOM) was separated into particulate organic matter (POM, >53 µm) and mineral associated organic matter (MAOM, <53 µm) by particle-size based fractionation method. We found that long-term NT effect and mode of residue C input (surface vs mixing) exerted distinct influences on residue mineralization and accumulation dynamics, possibly driven by different underlying mechanisms. 23.6 - 48.8 % of applied $^{13}C$ labelled plant residue C was mineralized to $CO_2$ with NTSA and CTSA treatment (surface applied residue) showing approximately two-fold higher mineralization than CTMIX (residue mixing). Consequently, the proportion of added residue C retained in SOC was greater under CTMIX. NTSA and CTMIX exhibited similarly reduced priming effects (P.E.), whereas P.E was strongly induced under CTSA, likely due to contrasting microbial responses. Residue derived C accumulation was limited to the soil surface (0-2.5cm) under NTSA and CTSA with larger C remaining (15-30%) in the POM fraction vs MAOM, indicating that surface residue application and NT systems preferentially promote residue-derived C accumulation in POM. Within the surface treatments, MAOM formation was also enhanced in CTSA compared to NTSA especially in 0-2.5cm which could be related to the differences in C saturation degree and microbial C assimilation ability. The findings from this study have important implications for C sequestration under long-term tillage management.

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# Land Use and Management Effects on Soil Health of Three Soil Types in the Republic of Serbia

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**ABSTRACT**

Land use and management practices affect soil health, and in the most cases intensive conventional management practices led to deterioration of soil properties and therefore, soil become less resilient to climate change. As organic agriculture is recognized as an approach that cares more about soil health and environmental protection (by use of only natural fertilizers and biopesticides), the aim of this research was to examine and compare the soil health of three soil types under different production systems: organic (from 5-10 years, and >10 years) and conventional, as well as to compare it with the soil health under natural soil (pasture).

Soil samples were taken from 20 farms, within three soil types (Chernozem, Humugley, and Stagnosol) with contrasting soil properties, particularly different in pH-values. In total, 160 samples were taken from 0-25 and 25-50 cm soil layers and prepared for the analysis of soil physical, fertility, and biological properties.

The results of the soil physical properties showed that land use systems (pasture and arable) affected aggregate stability and mean weight diameter (MWD), where MWD was significantly higher on pasture. However, bulk density and total porosity were the parameters the most sensitive to change of the system of the production (organic and conventional). In all three soil types, soil organic carbon (SOC) reserves were highest under pasture, following organic agriculture, and lowest under conventional agriculture. Moreover, the effect of organic agriculture on SOC was the most pronounced on Stagnosol. Regarding dehidrogenase and urease enzymatic activity, the highest values were measured on pasture on all three soil types. Moreover, on Humugley and Stagnosol, higher enzymatic activity was within organic agricultural practices compared to conventional.

In conclusion, although conversion from natural (pasture) to arable land led to loss of SOC and deterioration of soil health, the organic farming management has advantage compared to conventional in respect to soil biological parameters as enzymatic activity, especially on the less fertile soils.

**Key words:** Chernozem, Humogley, Stagnosol, SOC, Organic farming

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# Multispecies pastures and the soil science dilemma

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**ABSTRACT**

Increased plant diversity in pasture systems for animal production has positive effects on soil and animal health, and productivity. Diverse root systems can ameliorate poor soil structure, particularly at depth, and hence increase water availability in the soil profile, thereby improving plant production during the increasingly prevalent dry periods experienced in modern agricultural production. Our particular interest is multispecies pasture (MSP) swards for dairy production. The practice to implement a multispecies pasture varies; however, our study focussed on three dairy farmers in the high-rainfall zone of southern Victoria, Australia. These farmers, twice annually, inter-sow a multispecies seed mix of annual grasses, forbs and herbs, into existing perennial ryegrass pasture. Our study was primarily a partial budget analysis (Sale *et al,* in preparation). Transitioning to MSP was profitable, mostly attributed to the elimination of fertilizer, and importantly, with sustained milk production. Most agricultural systems acidify the soil, and particularly dairy systems due to heavy use of synthetic fertilizers and hence, require regular additions of lime to maintain soil pH. Farmers using MSP have been able to eliminate additions of lime, whilst maintaining satisfactory soil pH. Soil tests on one farm using MSP show alkalisation of an acidic soil profile, even at depth.

The dilemma for soil science is to explain how nutrient levels are maintained and sustained in these soils despite lack of fertilizer inputs, while diversifying plant species leads to alkalisation of the soil.

Most of the literature reports on the outcomes of plant diversification for crop and forage production and for animal health in grazing systems. However, little attention has focussed on the mechanisms for sustained nutrient availability from a dairy pasture soil with limited inputs of synthetic fertilisers. Management techniques that are likely to increase nutrient recycling include long rest periods between grazing, ensuring that adequate plant residue are retained on the surface, and concentrated confined grazing to ensure even spread of animal waste. However, the question is, will these well-fertilised dairy systems slowly run-down the soil fertility?

This poster summarises the findings of a critical literature review with the aim to compare the plant and soil biological pathways and nutrient cycling of a conventional N-fertilised pasture to an inter-sown multispecies pasture.

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# Four Decades of Soil Organic Carbon Dynamics in Seasonally Flooded Haor Wetlands of Northeastern Bangladesh amid Landscape Transformation

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## ABSTRACT

Long-term hydrological variability and land-use change have raised serious environmental concerns regarding the stability of soil organic carbon (SOC) and the transformation of ecologically significant wetland ecosystems. This study investigated historical landscape changes in the haor basin wetlands of northeastern Bangladesh and evaluated associated SOC dynamics driven by climate change and anthropogenic pressures. This study evaluated four decades (1985-2025) of landscape dynamics and SOC variability in the haor wetlands of northeastern Bangladesh by integrating multi-temporal remote sensing with field-based soil measurements. Land use and land cover (LULC) changes were analyzed at both regional and site-specific scales using Landsat, Sentinel-2, and European Space Agency's Climate Change Initiative (ESA-CCI) datasets processed in a geographic information system (GIS) environment. Changes in vegetation, surface water, flood-prone areas, and urban expansion were quantified and validated using the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Built-Up Index (BUI) for the 1985-2025 period. Field data from nine representative sites were used to assess SOC concentration and stock in the 0–15 cm soil layer. Between 2017 and 2025, the region experienced a 16.3% reduction in flood-prone areas and a 12.5% expansion of urban land, alongside increasing vegetation cover linked to agricultural intensification. NDWI declined by approximately 15% over the four decades of the study period, reflecting reduced inundation and altered hydrological regimes. Despite these changes, SOC stocks remained largely stable over the past 40 years, currently ranging from 30 to 122 Mg $ha^{-1}$ across sites. Higher SOC retention was consistently associated with clay-rich soils and recurring flooding, which maintained anaerobic conditions and limited organic matter decomposition. The findings highlight the critical roles of land-use decisions, hydrological regulation, and clay- mediated mineral protection in maintaining carbon security within lowland agro-wetland systems. Persistent anaerobic conditions have buffered soil organic carbon against land-use and hydrological changes in the haor wetlands. However, continued flood reduction and wetland conversion may undermine this stability. Overall, this study provides a mechanistic framework for integrating wetland carbon conservation into climate policy and land-use planning across floodplain and wetland ecosystems of South Asia. To safeguard these substantial carbon reserves, hydrologically informed wetland management, carbon-conserving agricultural practices, and strategic regulation of urban expansion are essential.

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# Vegetation-Driven Soil Organic Carbon Regulate Mercury Accumulation in Karst Soil Profiles

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**ABSTRACT**

Vegetation regulates soil mercury (Hg) sequestration primarily through the formation and transformation of soil organic carbon (SOC) pools, yet the mechanisms underlying this control remain poorly quantified, especially in reactive karst landscapes. Here, we examine Hg distribution and speciation across cropland, grassland, and forestland soil profiles in a typical karst catchment, combining measurements of total Hg (THg), dissolved Hg (DHg), mineral-associated organic carbon (MAOC), particulate organic carbon (POC), iron-associated organic carbon (Fe-OC), stable carbon and nitrogen isotopes with partial least squares structural equation modeling (PLS-SEM) and multivariate nonlinear regression analysis (MNRA). We show that forestland soils accumulate the most Hg, with topsoil concentrations exceeding 110 μg $kg^{-1}$ and profile enrichment surpassing 154.5%, due largely to the accumulation of MAOC. The role of Fe-OC in Hg retention strengthens markedly during succession from cropland to forestland, underscoring mineral adsorption as a key sequestration pathway in karst systems. Vegetation cover, soil depth, pH, and iron oxides collectively modulate Hg stability by governing SOC composition: stable SOC promotes sustained sequestration, whereas labile SOC may facilitate Hg release via microbial activity. Globally, this SOC control dominates in unpolluted areas, whereas polluted areas are influenced mainly by direct inputs. Our findings reveal that vegetation restoration enhances sustained soil Hg storage, while agricultural use may elevate mobilization risks from reactive carbon pools. These results highlight the need to incorporate vegetation cover feedbacks into Hg risk assessments and global cycling models.

**Keywords:** Mercury accumulation, Vegetation covers, Whole- soil- profile, SOC, Karst

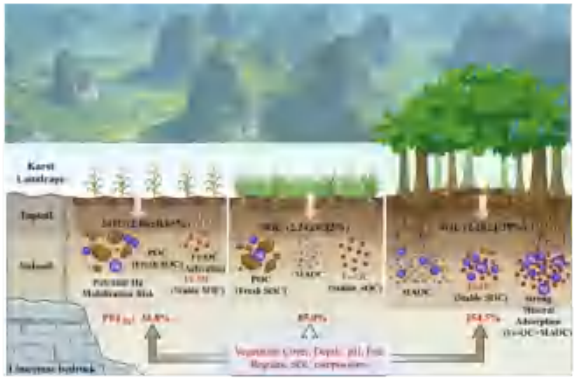
Highlight:

(1) Topsoil under different vegetation covers shows significant Hg enrichment, with Hg content decreasing with depth and forestland showing the highest enrichment intensity.

(2) Contributions to soil Hg accumulation follow the order MAOC > Fe-OC > POC, with mineral adsorption-protection as the key mechanism.

(3) The regulatory factors for Hg accumulation shifted from SOC in non-polluted areas to geological background and exogenous inputs in polluted areas.

(4) Vegetation restoration drives global greening and enables sustained stable Hg sequestration via promoting MAOC formation and providing a nature-based solution to historical Hg remobilization.



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# THE LEGISLATIVE BASIS FOR SOIL PROTECTION – THE RED SOIL BOOK

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**ABSTRACT**

The legislative basis for the creation of the Red Soil Books in Russia is the Federal Law "On Environmental Protection" (January 10, 2002), which states that the Red Soil Book of the Russian Federation and the Red Soil Books of the constituent entities of the Russian Federation are established to record and protect rare and endangered soils. Article 62 of this Law states that the procedure for classifying soils as rare and endangered, as well as the procedure for establishing land use regimes for land plots whose soils are classified as rare and endangered, are determined by law. However, regulatory documents and methodological recommendations governing the compilation and maintenance of Red Data Books of Soils in Russia have not yet been developed. Only general methodological approaches are found, substantiated in scientific articles and monographs. The reasons for this situation are quite objective, as the soils of different regions of the country differ in their genesis, properties, fertility, and the degree of agricultural development and transformation.

Regional Red Data Books of Soils should serve as the legislative basis for scientifically based protection of the soil cover of each region. Uniform principles for compiling Red Data Books of Soils have been developed for the entire country; however, in regions with specific soil cover characteristics, the development of this document may require specific considerations.

For example, for regions with a high percentage of cultivated land, identifying areas for the conservation and study of Red Data Book soils is particularly problematic. Here, the most fertile soils are also the most actively used in agriculture, which significantly alters their morphology and properties. For example, in the Rostov Region, such soils are chernozems. In fact, such soils in their native form remain only within the boundaries of Specially Protected Natural Areas, and the areas they occupy are so small that they can even be classified as endangered soils.

For regions with a high proportion of cultivated land, such as the Rostov Region, the virtual absence of virgin soil varieties poses several additional challenges. Therefore, in the process of developing the Red Data Book of Soils for the Rostov Region, special attention is being paid to the first section of the Red Data Book of Soils—the identification of soil standards. Given the high intensity of chernozems used in the Rostov Region and their significant importance in ensuring food security for the country, it is essential to ensure high-quality monitoring to prevent their degradation.

**Acknowledgment**

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# Soil Physical and Chemical Responses Along a Pasture-to-Forest Succession in the Alps

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**ABSTRACT**

Forest expansion following agro-pastoral abandonment is widespread in European mountains and has been further accelerated by recent climate warming (Piccinelli et al., 2020). Previous studies show that woody encroachment does not necessarily increase soil carbon, as accumulation often occurs mainly in woody biomass while soil responses remain variable and context-dependent (Guidi et al., 2014). Recent evidence also indicates that forest expansion alters soil aggregation, reducing microaggregate (Ortiz et al., 2022). Climate, local environmental conditions, and land management strongly modulate these responses, highlighting the lack of a universal pattern and the need for site-specific studies in mountain ecosystems. In this study, we investigated how soil physical (bulk density, aggregate stability) and chemical (total C and N, inorganic N forms, available P) properties change along a gradient of a pasture recolonization by larch, from an actively managed pasture to a mature forest, through a case study in the Northwestern Italian Alps (LTER research site Tellinod, Aosta Valley Region, NW Italian Alps; ~2100 m a.s.l.). Topsoil (0–15 cm) was sampled in five plots representing successive recolonization stages (started around 2008), for a total of 50 samples. Our results show that soil physical and chemical properties varied clearly along the gradient. Bulk density was highest in the grazed pasture, while aggregate stability was lower and soil erodibility (K) higher in the mature forest. pH showed no significant differences, whereas total C and N were slightly lower in the pasture and significantly reduced in the mature forest. Ammonium, nitrate, and dissolved organic carbon (DOC) were lowest in the pasture and mature forest, indicating that successional stages differ in their activity within the carbon and nitrogen cycles, with nutrient availability highest in intermediate stages. Reduced total C in the mature forest likely contributes to lower aggregate stability and higher erodibility. These findings highlight the tight coupling between soil structure and fertility during woody encroachment and underscore the importance of local studies for sustainable land management and biodiversity conservation in alpine environments.

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# Replacing periodic burning with improved forages reshapes soil carbon and nitrogen dynamics and tree–soil interactions in Colombian savannas.

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## ABSTRACT

Periodic burning to promote grass regrowth is a common management practice in extensive cattle ranching in Colombian savannas, leading to soil degradation and unsustainable landscapes. The introduction of improved grass forages with higher palatability, combined with rotational grazing, allows burning cessation and enhances productivity. However, the effects of this management shift on soil carbon (C) and nitrogen (N) cycling remain poorly studied. In tropical savannas, native trees represent important inputs of organic matter to soils and can strongly influence C and N dynamics. Here, we assessed the impact of replacing burning with improved forages on soil C and N dynamics in the Vichada Department, Colombia and evaluated the role of native trees (*Curatella americana*) in shaping these dynamics.

We compared two contrasting managements using a fence-line approach: a conventional system with annual burning, continuous grazing, and a low stocking rate (0.006 livestock units (LU) $ha^{-1}$; *conventional*), and an improved system where an improved grass forage (*Urochloa humidicola*) was introduced 10 years ago, burning was ceased, and rotational grazing with high stocking rate (1 LU $ha^{-1}$) was implemented (*improved*). In each system, eight trees located at least 100 m apart were selected. Soil samples were collected at three depths (0-10, 10-20, and 20-30 cm) and at two distances from the tree trunk 0.5 and 2.5 times the canopy radius, (representing beneath and outside the tree canopy, respectively). Tree leaves and pasture biomass were also sampled. Soil and plant samples were analyzed for total C and N, as well as $\delta^{13}C$ and $\delta^{15}N$.

Soil C concentration (0-30 cm) was significantly higher under improved than under conventional management (16.2 vs. 13.2 g C $kg^{-1}$), likely due to burning cessation. This increase was mainly driven by higher soil C beneath trees in the improved system compared to the conventional (16.8 vs. 13.0 g C $kg^{-1}$). Burning cessation increased native tree growth and litter inputs to soil, as confirmed by higher soil $\delta^{13}C$ values (+0.73‰) beneath trees in the improved system, indicating a greater contribution of C derived from $C_3$ trees (−29.67‰) relative to $C_4$ grasses (−13.71‰). Soil $\delta^{15}N$ values were significantly lower under improved management (5.84‰) than under conventional (6.46‰), suggesting reduced N losses following fire burning cessation, as gaseous N losses during burning are $^{15}N$-depleted. This reduction in N losses was reflected in higher soil N concentrations and lower C:N under improved management.

Overall, replacing burning with improved forages and rotational grazing increased soil C and N concentrations, enhanced tree contributions to soil C accrual, and reduced N losses, mitigating the environmental impacts of cattle ranching while increasing system sustainability and productivity and supporting savanna conservation by sparing land.

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# The effect of winter-sown oat catch crops on nitrogen leaching after livestock grazing

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**ABSTRACT**

Grazing of livestock on high-yielding annual forage crops (e.g. fodder beet, kale) can have detrimental effects on water quality outcomes, particularly through mineral-nitrogen (N) leaching with reported losses of up to 180 kg N/ha. This is largely because of: 1) high N returns in urine patches under high livestock densities, and 2) bare soil with no plant N uptake for long periods under wet winter-early spring conditions.

The objective was to test the effect of oat catch crops establishment and associated sowing timings and tillage practice on mineral-N leaching losses following simulated winter grazing, compared with typical fallow conditions.

Repeat field leaching experiments over two years (2021 and 2022) using 40 intact soil monolith lysimeters (50 cm diameter x 70 cm deep) were conducted in Southland, New Zealand. Simulated livestock treading was applied to the Waikiwi soils (Typic Firm Brown Soil) inside the lysimeters, followed by a winter application of fresh cow urine (equivalent to 200 kg N/ha). Imposed treatments included early (Jul/Aug; winter) and late (Sep/Oct; spring) cultivation at 10 or 25 cm depth compared with a non-cultivated winter fallow control. Oats were then hand-sown in 50% of all cultivated lysimeters in winter or spring, and drainage water was collected and analysed for mineral-N (ammonium and nitrate) until winter oats reached green-chop silage maturity (Nov/Dec).

Winter-sown oats were shown to reduce mineral-N leaching by 35–61% compared with the fallow control. Delayed sowing until spring achieved similar reductions (28–54%), indicating a potentially longer window of opportunity to establish catch crops for reducing mineral-N leaching in colder climates. Cultivation increased leaching in some cultivated, non-seeded plots when compared with the fallow control (by up to 76%), likely from enhanced N mineralisation; however, oats were shown to mitigate this added risk. Reductions in mineral-N leaching were attributed to the 62–137 kg/ha of N captured in aboveground biomass of oats, where yields were between 2.7 and 12.8 t DM/ha. Oat yields and N uptakes were on average 6.1 t DM/ha and 35 kg N/ha greater with early sowing than late sowing.

We conclude that sowing oat catch crops in cold regions of New Zealand can significantly reduce mineral-N leaching losses from winter forage crop grazing, despite the added risk of N mineralisation from the practice of catch crop cultivation in winter.

**Acknowledgments**

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# Effects of Different Land Use Types on Soil–Microbial Ecochemical Stoichiometry in Agro-Pastoral Ecotones

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**ABSTRACT**

Ecological stoichiometry is an important representation for understanding nutrient cycling and balance in ecosystems. The agro-pastoral ecotone, as a key interface connecting the two major food production systems of farming and animal husbandry, has become an ecologically fragile zone due to land use changes caused by the frequent replacement of cropping systems. However, the response patterns of soil-microbial ecological stoichiometric characteristics to different land use types in the agro-pastoral ecotone remain unclear. This study focused on the agro-pastoral ecotone in Inner Mongolia and selected six typical land use types: no grazing (NG), rotational grazing (RG), continuous grazing (CG), grass-field rotation (CT), continuous maize farmland (NT), and abandoned land (LH). By measuring indicators such as soil organic carbon, total nitrogen, total phosphorus, and microbial biomass carbon, nitrogen, and phosphorus, the study systematically analyzed the effects of land use types on soil and microbial stoichiometric ratios and their driving mechanisms. The results showed significant differences in soil nutrient content and stoichiometric ratios among different land use types, with the highest SOC and C:Psoil and N:Psoil under NG, the highest TN and TP under RG, and the highest C:Nsoil under LH. CT treatment significantly increased MBC, C:Nmic, and C:Pmic, while CG treatment significantly increased MBP but had the lowest C:Nmic. The qMBC was highest under CT, qMBP was highest under CG, and the chemical stoichiometric imbalance was highest under LH. Redundancy analysis revealed that the C:Pimb, N:Pimb, and C:Pmic were the main drivers of microbial entropy changes, indicating that phosphorus supply-demand imbalance is a key limiting factor restricting soil microbial growth and metabolic efficiency in this region. This study elucidates the response patterns of soil-microbial stoichiometric characteristics to land use types in the agro-pastoral ecotone and finds that CT treatment is most advantageous in maintaining soil carbon storage and enhancing microbial resource utilization efficiency, while LH treatment leads to severe stoichiometric imbalance. In the future strategies for cropping system replacement in the agro-pastoral ecotone, phosphorus limitation should be a key consideration to stabilize nutrient cycling in the soil-microbial system.

**Key words**: Land use patterns; soil microbial biomass; ecological stoichiometry; microbial entropy; stoichiometric imbalance

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# Iceland's degradation history is taking a hopeful turn through revegetation and ecosystem monitoring

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**ABSTRACT**

Iceland, a 100,000 km² volcanic island in the North Atlantic, has experienced diverse ecosystem states over the last millennium. Before the human settlement, almost half of the country consisted of mountain birch woodlands and heathlands. However, following the settlement the vegetation cover got significantly reduced due to both anthropogenic and environmental factors, and interactions thereof. Today, roughly 40% of the country is considered degraded or highly degraded with large areas where the entire soil profile has been completely lost. This is due to both inherited Andosol properties and land management. Andosols can have little particle cohesion and low bulk density, resulting in high erosion risk when exposed. At the same time, they have high water and carbon retention potentials, both contributing to their relatively high fertility. This suggests that the currently vast degraded areas have considerable potential for carbon sequestration through revegetation. Revegetation projects have been ongoing since 1907 with the establishment of the Soil Conservation Service of Iceland, now Land and Forest Iceland. These areas have been systematically monitored with respect to inputs and soil carbon yields since 2007, when Iceland selected revegetation as a countermeasure under the Kyoto protocol. To achieve this a sampling grid of 1x1 km² was superimposed on a map of Iceland followed by selecting all points intersecting with revegetation areas larger than 0.5 ha and active since 1990. These potential sampling points were visited and those qualifying for sampling then selected, in total 640 points. Permanent 10 x 10 m sampling plots were established at each location and sampled during 2007-2011. The sampling campaign was repeated in 2018-2022 with both revisiting existing points and establishing new or expanded areas. In each plot, five 50x50 cm randomly distributed subplots were laid out for assessing species richness and vegetation cover using a modified Braun-Blanquet scale, followed by soil sampling at 0-5, 5-10, 10-20, and 20-30 cm depths. Both total carbon and total nitrogen were analyzed using the Dumas method. The results from this ongoing project provide invaluable data on the feasibility of different reclamation approaches under various conditions and soil carbon sequestration. Current results show a general increase in carbon stocks, but they vary with site conditions and inputs. Further data analysis will focus on identifying the efficient ways to revegetate degraded areas and how to facilitate consequent vegetation succession.

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# Century-long spatiotemporal variation in cropland soil erosion and the roles of anthropogenic factors in the Tuojiang River Basin, China

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## ABSTRACT

Evaluating the long-term soil erosion dynamics and their responses to anthropogenic forcing at the regional level is crucial for assessing the impacts of soil conservation efforts and informing future policy development. The soil erosion issue is particularly severe in southwestern China due to its large hilly areas and extensive human activities. However, due to the lack of long-term records, there has been insufficient evaluation of the historical variations in cropland erosion across the spatial scales of decades and centuries, which hinders a comprehensive understanding of the main drivers and their effects. By using the Revised Universal Soil Loss Equation model in combination with remote sensing-based multisource data, the spatial and temporal evolution of cropland soil erosion in the Tuojiang River Basin (TRB) in China from 1911 to 2017 is assessed in this study. We also employl geographically and temporally weighted regression (GTWR) to assess the spatial and temporal heterogeneity ofl the anthropogenic factors impacting cropland soil erosion in the TRB from 1911 to 2017. The study resultsl indicate that (1) in the past century, an average of 77.70% of the TRB has exhibited a slight soil erosion level,l with the upper stream experiencing a higher rate. (2) The amount of soil erosion increased slightly from 1911 tol 1960, dramatically increased by 70.07% from 1960 to 1980, and then decreased by 34.759 from 1980 to 2017. Cropland soil erosion mainly occurred in the upper stream, but it has been expanding to the downstream regionl since 2000. The high rate of cropland cultivation in the densely populated upper reaches is the main cause of accelerated erosion. (3) The increase in cropland soil erosion has primarily been driven by population growth and cropland expansion with contrary effects, reflecting a complex interplay of diverse natural and anthropogenic mechanisms. Spatiotemporal differentiations in the influences of both factors became evident with thel economic reform and implementation of ecological conservation policies that have been occurring since 1980.l These results can provide valuable insights for decision-makers for better understanding the long-term evolutionl of cropland soil erosion and the implementation of targeted soil conservation measures.

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# Soil Properties of Oil Palm Based Agroforestry System

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**ABSTRACT**

Ecological degradation from oil palm monocultures stems from extensive land clearing and the promotion of single-species stands. Oil palm agroforestry is an alternative to restore soil health that is commonly diminished through monoculture management practices. This study evaluates the soil chemical and biological characteristics of an oil palm agroforestry system established in 2022 in Sabah, Malaysia. In the agroforestry system, the incorporation of native tree species increases the planting density and diversity of the system. We hypothesized that increased aboveground vegetation density and diversity would induce changes in soil biological and chemical properties. The experimental design compared three management systems: oil palm monoculture, oil palm agroforestry, and an adjacent riparian zone. Soil replicates (n=5) were analyzed for soil chemical properties (total nitrogen (N), total and available phosphorus (P), total potassium (K), total carbon (C)), soil bacterial abundance and diversity using 16S rRNA amplicon sequencing.

Results showed that while overall soil microbial alpha diversity did not differ significantly across management systems, LefSe Biomarker Analyses revealed that the proportion of unique taxa increased with vegetation diversity (riparian > agroforestry > monoculture). Soil acidity, total N, available and total P, and total K were significantly higher in the cultivated zones (monoculture and agroforestry) than in the riparian zone (Table 1). From this result, soil chemical properties were likely influenced by fertilizer management and not by aboveground vegetation differences. Total soil carbon content (Table 1) remained consistent across all sites. However, functional profiling of the microbiome indicated that the riparian and agroforestry systems possessed a higher abundance of carbon degradation pathways. This suggests that more diverse aboveground litter inputs are already shaping the microbial functional potential to decompose a broader range of organic substrates.

These findings are crucial for the ongoing evaluation of the ecological trajectory of an oil palm cycle, which typically lasts for 25 years. As the palms in this study are currently juvenile, more changes in soil properties are expected as palms grow and approach maturity. Ultimately, this study provides evidence that alterations in aboveground diversity and density can influence the soil properties of oil palm-based landscapes.

Table 1.

| Soil test | AFS | Mono | Riparian |
|---|---|---|---|
| pH | 4.15±0.22 | 4.46±0.13 ** | 4.8±0.23*** |
| Total P (%) | 0.035±0.010 | 0.038±0.015 | 0.018±0.008*** |
| Av. P (mg/kg) | 4.429±3.143 | 8.169±6.553 | 1.62±1.62** |
| Total K (%) | 0.965±0.089 | 1.009±0.121 | 0.792±0.145** |
| Total N (%) | 0.14±0.08 | 0.17±0.05 | 0.09±0.05** |
| Total C (%) | 1.55±0.72 | 1.39±0.81 | 0.97±0.68 |

**, *** at $p < 0.05$, and 0.01 respectively.

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# Aggregate-Size-Specific Carbon and Nitrogen Responses to Reduced and Deep Tillage in Japanese Andosols

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**ABSTRACT**

Tillage strongly influence soil aggregate structure and nutrient dynamics. However, these processes remain poorly characterized in Japanese natural farming systems. In particular, direct comparisons of reduced tillage (RT) and deep tillage (DT) at aggregate size-specific Total Organic Carbon (TOC) and Total Nitrogen (TN). Although mechanistic studies in Andosols have clarified soil organic matter (SOM) stabilization pathways, the effect of tillage on nutrient partitioning within aggregates under real farm conditions remain unclear. This study investigates aggregate-size specific carbon and nitrogen responses to tillage effects in Japanese natural vegetable farms.

Soil profile surveys and pre/post-cultivation sampling were conducted in RT and DT farms in Ibaraki Prefecture. Soil aggregates were fractionated by wet sieving across aggregate fractions (63 µm – 2mm), and aggregate-associated TOC and TN concentrations, along with basic physicochemical properties, were analyzed.

The results from RT soil showed well-developed soil structure, higher TOC, TN and markedly higher available Phosphorous among the study sites. RT significantly increased microaggregates and demonstrated strong size-dependent shifts in TOC and TN, including increases in 63 µm and 500 µm fractions and reductions in 2 mm fraction. In contrast, DT exhibited disturbed soil structure with weakened aggregate stability, declining TOC and TN with depth, and lower Cation Exchange Capacity (CEC). DT reduced microaggregates and increased larger, unstable aggregates. Overall, TOC and TN distributions were more strongly differentiated by aggregate size than by tillage practice alone. Reduced tillage preserved clear-size specific patterns of TOC and TN, whereas deep tillage diminished these differences in Japanese Andosols.

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# Soil carbon and nitrogen dynamics in mechanized maize-based intercropping

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## ABSTRACT

Crop diversification offers a pathway toward sustainable agriculture. Traditional intercropping systems, such as the "Three Sisters" intercropping and maize-bean systems, may offer several ecological benefits but are often incompatible with mechanization in large-scale systems. This study investigates the impact of traditional intercropping on soil carbon and nitrogen dynamics, and associated soil microbiology. Specifically, it evaluates whether row-based designs of traditional maize-based intercropping systems can sustain yields under low-input Mediterranean farming. Field experiments in Central Portugal employed a randomized block design with replicates to compare five treatments: maize (M), beans (B) and squash (S) monocrops, and maize-beans (MB) and maize-bean-squash (MBS) intercropped. Planting densities were: 80,000 plants $ha^{-1}$ for M; 53,333 maize and 26,666 bean plants $ha^{-1}$ for MB (2:1 ratio); and 53,333 maize, 26,666 bean, and 5,333 squash plants $ha^{-1}$ for MBS (10:5:1 ratio). The crops were sown in rows, facilitating mechanization. No nitrogen fertilization was applied during the cropping season. Crop health was monitored through chlorophyll analysis. At the maize VT phenological stage, soil carbon emissions were measured using LI-7810 Trace Gas Analyzer. The abundance of N-fixing bacteria was determined using standard microbiological method, and the results were expressed as colony-forming units per gram of soil ($10^5$ CFU $g^{-1}$). N-fixing bacterial populations in MB (43.0 CFU) and MBS (43.7 CFU) were significantly higher than in M (32.7 CFU). Similarly, soil carbon emissions in MB and MBS (3.3 and 3.4 µmol $m^{-2}$ $s^{-1}$, respectively) were significantly higher than in M, reaching parity with the B. This suggests that intercrops maintained high metabolic rates despite lower plant densities. Chlorophyll analysis revealed a "stay-green" effect in intercropped beans, which delayed senescence by 26 days compared to B. This sustained soil metabolic activity facilitated a compensatory growth response, enabling intercropped maize to significantly outperform monocropped plants on an individual basis. Consequently, intercropped maize achieved a total yield comparable to the monocrop despite a 33% lower plant density, representing to a 2.7-fold increase in individual plant productivity relative to M. Ultimately, this synergy allowed the MB system to achieve the highest land equivalent ratio (LER) and water use efficiency (1.96 and 10.6 kg/ha/mm, respectively), while the MBS system was limited by the competitive exclusion of squash (zero yield), resulting in a lower LER (1.33). These findings show that traditional intercropping acts as a biological primer for N-deficient soils, where optimized microbial synergies and temporal niche differentiation stabilize productivity and resource-use efficiency without the need for synthetic fertilizers.

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# Enhancing soil-wheat resilience with biochar-based microbial fertilizer application under deficit irrigation

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## ABSTRACT

Affected by global climate change and long-term unreasonable planting and fertilization, agricultural production is increasingly threatened by soil degradation, nutrient depletion, and water stress. This study aims to reveal the combined effects of biochar-based microbial fertilizers and irrigation levels on soil quality and wheat growth, providing essential insights for sustainable agricultural management. This study conducted a pot experiment, including four application levels of biochar-based microbial fertilizer and four irrigation levels. The effects of biochar-based microbial fertilizer on soil nutrients, wheat physiological and biochemical indicators, and yield are explored. Biochar-based microbial fertilizers under different irrigation levels significantly enhanced nutrient utilization efficiency, stabilized organic matter, and improved soil bacterial community composition. Under varying irrigation levels, biochar-based microbial fertilizer enhanced wheat photosynthesis, increased soluble protein accumulation, and effectively boosted wheat yield. This study reveals the mechanisms by which biochar-based microbial fertilizers improve soil quality and clarifies their potential to promote wheat physiological growth and increase yield under different irrigation levels, offering a promising sustainable solution for building efficient soil-crop systems.

**Acknowledgments**

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# Microbiome-enabled biochar mitigates drought impacts and improves soil nutrient availability and maize growth in under deficit irrigation

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## ABSTRACT

Water crisis is restricting the production of maize, and deficit irrigation, though essential in saving water, is likely to enhance nutrient limitations and physiological drought stress, which accelerates the decay in growth and yield as irrigation is reduced. The researchers measured the capacity of a biochar-based microbial fertilizer (BMF) in mitigating the impact of drought through the enhancement of soil physical structure, nutrient buffering, as well as rhizosphere functionality and, in turn, enhancing the water productivity of maize under conditions of controlled deficit irrigation. Factorial pot experiment entailed a mixture of various rates of irrigation of well-watered and severe deficit along with the graded rates of BMF application. The parameters of maize growth and yield have been measured together with soil physical parameters, significant chemical parameters (pH, organic carbon, available nutrient forms, mineral forms of nitrogen), and biological functioning (enzyme activity and proxies of microbial activity). The decreasing monotonic shifts in plant height, leaf expansion, biomass development, and reproductive efficiency in the unamended treatment were brought about by the reduction of irrigation. Comparatively, BMF structured these trends of droughts by enhancing water holding capacity and hydraulic conductivity of the soil, organic carbon and cation exchange capacity, and enhancing nutrient availability and retention. BMF chemically and biologically secured the mineral N supply and maximized the conservative nitrogen cycling that preferably operated canopies in the long term and reduced the damage with limited water due to stress. Their findings give a mechanistic foundation for integrating biochar-based microbial fertilizer in deficit irrigating in order to co-optimize the condition of the ground and the nutrient retention and maize strength, and offer a sustainable approach to enhancing disciplinary cultivation in a water-restricted setting on a large scale.

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# The effect of organic farming systems and cover crops on soil health after land use change in southeastern USA

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**ABSTRACT**

Land use change can alter soil properties and soil health. Increased population pressure and related food needs are the most important drivers of conversion of natural vegetation to cultivated land. Converting native vegetation land to high tunnel production is a very economical and high-return land use management. Research on soil properties under land-use change could help managers to clarify the status of soil health and make timely appropriate management decision, which is of great significance for the sustainable utilization of land resources. The effect of organic farming system and cover crops on soil health indicators in high tunnels after land-use change, however, is not well understood. Field experiments were conducted to determine the effects of oraganic farming systems and winter-planted cover crops on soil health of vegetable production systems in humid environments. We tested soil bulk density, organic carbon, total nitrogen, extractable phosphorus, extractable potassium, available water content, saturated hydraulic conductivity and conducted soil health assessment. The results can provide a References for farmers to manage soil health in the Southeast United States.

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# Oil Palm Height, Frond Development and Chlorophyll Responses under Monoculture and Nauclea subdita Agroforestry

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**ABSTRACT**

Oil palm (*Elaeis guineensis*) is predominantly cultivated as a monoculture, involving repeated fertiliser applications, resulting in lower soil health. A viable alternative to monoculture oil palm is oil palm agroforestry, which can potentially increase soil health by better supporting the soil microbial ecosystem, leading to improved crop growth. However, oil palm agroforestry has never been tested in Malaysia, prompting this study to assess whether agroforestry implementation would influence oil palm growth compared to monoculture. In this study, two agroforestry treatments were established: one interplanted native tree (*Nauclea subdita*) between two palms (low-density), and two interplanted native trees between two palms (high-density). Growth parameters (height, frond number, and chlorophyll content) were measured twice per year. Significant treatment effects were observed only at the first measurement for oil palm height and frond number ($p<0.05$). Oil palm height in the high-density treatment did not significantly differ from that in monoculture or low-density agroforestry, indicating an intermediate height response. Meanwhile, frond number was considerably higher in high-density agroforestry than in monoculture or low-density agroforestry, indicating altered growth under agroforestry conditions; however, there was no difference in relative chlorophyll content. Comparisons of relative growth between treatments at the two measurement times showed differences; low-density agroforestry had higher relative frond growth than the higher-density treatment (similar to the monoculture), but lower chlorophyll values than the monoculture. These findings provide early insights into the effects of oil palm growth responses in monoculture and agroforestry, where low-density agroforestry showed a comparable growth response to monoculture; however, additional trees altered growth patterns. This suggests that the early influence of agroforestry on oil palm performance can only be observed when more than one tree is interplanted between palms.

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# Regional scale mapping of a soil health index using machine learning and digital soil mapping with driver attribution

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**ABSTRACT**

Soil health provides a fundamental basis for sustaining ecosystem functioning, enabling sustainable agricultural development, and safeguarding food security. Its conceptual scope has expanded from a narrow focus on "soil fertility" to a more integrative capacity encompassing productivity maintenance, environmental regulation, and ecosystem service provision (Doran et al., 1996; Lehmann et al., 2020; Bünemann et al., 2018). However, conventional soil health assessments typically depend on sparse sampling and laboratory measurements, which limits their ability to characterize continuous regional-scale spatial patterns and to disentangle heterogeneous driving mechanisms. To address this bottleneck, this study selected Hailun City, a representative agricultural county in the black soil region of Northeast China, as the test area. A soil health index (SHI) was developed using physicochemical and biological indicators from the 0–20 cm layer, and digital soil mapping (DSM) coupled with machine-learning algorithms was employed to shift from "field-scale diagnosis" to "regional-scale inference," providing actionable and quantitative technical support for black soil conservation and cropland quality improvement (Nabiollahi et al., 2018; Zeraatpisheh et al., 2020).

We established an end-to-end workflow comprising "indicator reduction–index construction–machine-learning mapping–accuracy assessment–driver analysis." First, principal component analysis and correlation-based screening were used to derive a minimum data set (MDS), thereby reducing multicollinearity and redundancy and improving index robustness (Li et al., 2019; Iheshiulo et al., 2024). Next, linear and nonlinear scoring functions were applied to transform indicators with different units into standardized scores ranging from 0 to 1, which were then aggregated (e.g., via weighted integration) to construct the SHI and enhance sensitivity and interpretability with respect to soil condition changes (Andrews et al., 2002, 2004). For spatial prediction, we integrated terrain-, remote sensing–, soil-, and management-related environmental covariates, and implemented random forest (RF), gradient boosting machine (GBM), and support vector machine (SVM) models to simulate and compare the spatial distribution of SHI, thereby producing a reproducible regional-scale soil health mapping workflow (Vasu et al., 2016; Zeraatpisheh et al., 2020).

The results revealed marked differences in model performance for representing SHI spatial patterns: RF achieved the highest accuracy ($R^2$ = 0.61), outperforming GBM ($R^2$ = 0.49) and SVM ($R^2$ = 0.43). The RF-derived SHI map exhibited strong consistency with the distribution of black soils in Hailun, current land-use patterns, and topographic gradients, and more reliably captured spatial heterogeneity and potential key control zones of soil health within the black soil region. Overall, the proposed integrated framework—linking SHI construction, machine-learning-based mapping, and mechanistic interpretation—offers both scientific rigor and operational feasibility. It enables conversion of limited point observations into decision-support products for local implementation, and provides a transferable pathway for zoned management of black soil conservation, cropland quality enhancement, and sustainable agricultural management (Nabiollahi et al., 2018; Iheshiulo et al., 2024).

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# Transformation patterns of precipitation-soil water-crop water in karst regions and their impact on maize yield

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## ABSTRACT

In recent years, the southwestern karst region of China has experienced frequent sudden, seasonal, and regional droughts, which have exerted serious direct and indirect impacts on agricultural production, the ecological environment, and socio-economic development. Research on the formation mechanisms of agricultural drought in karst regions remains limited, particularly with respect to the transformation processes among precipitation, soil water, and crop water, and the systematic effects of these transformation processes on maize yield are poorly understood. This study elucidates the dynamic transformation patterns among precipitation, soil water, and crop water during the maize growing season and clarifies the impact of dynamic changes in precipitation, soil water, and crop water on maize yield. During the summer maize growing season, the intra-annual temporal variation patterns of precipitation, crop water, and soil water are similar, with values in July–August exceeding those in June and September. This pattern is primarily attributable to the fact that peak precipitation in the study area predominantly occurs in July and August. Across different regions, a decrease in precipitation during July–August leads to corresponding decreases in crop water demand, while soil water exhibits varying degrees of increase, indicating that a portion of precipitation is transformed into infiltrated soil water. Moreover, Correlation coefficients between soil water, crop water demand, and summer maize grain yield all exceed 0.62, and these correlations are stronger than those between precipitation and summer maize grain yield. In most regions, summer maize yield is most strongly correlated with crop water demand, followed by soil water. The findings of this study have great implications for agricultural drought resistance and efficient water resource utilization in karst regions.

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# Decision support tool for improved nutrient and carbon management at farm level

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**ABSTRACT**

Soil nutrient imbalances have negative impacts on the environment and crop yield. It is therefore of major importance that farmers make sustainable soil nutrient and carbon management decisions by implementing measures that stimulate soil quality, water quality, crop productivity, and biodiversity, and minimize GHG emissions. Given the fact that the effectiveness of measures strongly varies over space and time, it is important to increase our insight into the current and potential soil nutrient and carbon budgets, i.e. difference between inputs and outputs, and the impact of measures affecting these budgets and associated impacts. This study presents the NutriFarm model as a decision support tool that can evaluate the effect of various soil, crop and nutrient measures affecting the five abovementioned goals. The tool not only evaluates macro-nutrients (N, P, K), but also S, Ca, Mg, Zn, and Cu, and soil organic carbon (based on the RothC model) and its interactions with soil organic nitrogen. The tool covers EU-27, the United Kingdom and Switzerland, and is aimed to be used by farmers or farm advisors. This tool is freely available on the NutriPlatform, i.e., a platform that was built as part of the NutriBudget project (Grant agreement ID: 101060455). This platform can be used by multiple stakeholders, because it also includes the results of ten different roadmaps for policymakers. This stimulates the dialogue between farmers and policymakers on the transition towards a sustainable agricultural sector.

# Optimized fertilization strengthens the soil health–yield relationship by enhancing biological activities

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**ABSTRACT**

Chemical fertilizers support crop production, yet their long-term consequences for soil health, particularly the biological functions, remain poorly understood. Here, we used four long-term (≥ 10 years) field experiments with contrasting fertilization regimes evaluate the effects of chemical fertilization on soil health, microbial functions, and their linkages to wheat productivity. We found that improved fertilization practices, characterized by moderately reduced fertilizer inputs, significantly enhanced soil health and also led to a modest increase in wheat grain yield compared with typical farmer fertilization practices, primarily through enhanced biological functions. Bacterial and archaeal phylogenetic diversity, but not fungal diversity, was positively associated with the soil health index. Notably, rare bacterial taxa were the key drivers of biogeochemical functions, including carbon, nitrogen, phosphorus, and sulfur cycling. Appropriate fertilization rates (255 kg $ha^{-1}$ ~ 375 kg $ha^{-1}$) promoted positive linkages among soil health, biological functions, and wheat yield via increased grain number. In contrast, no significant effects were observed in the excessive fertilization treatment (420 kg $ha^{-1}$ ~ 870 kg $ha^{-1}$). Collectively, our findings emphasize the role of soil microbiome in mediating soil health and crop productivity, underscoring the necessity of integrating biological indicators into nutrient management strategies for sustainable agricultural intensification.

**Acknowledgments**

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# Grassland legacy effects regulate nutrient leaching losses in cropland phases in long-term grassland-crop rotations

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## ABSTRACT

Grassland–crop rotations (GCR) are increasingly promoted as a sustainable strategy to enhance soil organic matter and nutrient retention. However, the influence of differently managed grasslands on nutrient leaching in subsequent croplands, i.e. their legacy effects (LE), remain poorly understood. In this 15-year field experiment in a temperate agroecosystem (Lusignan, France), we evaluated how grassland LE influences leaching losses of six nutrients ($NO_3$-N, PO4-P, K+, Ca2+, Mg2+, and $SO_4$-S). Three grassland management practices in GCR varying in grassland duration and nitrogen fertilization were investigated and compared to continuous grassland and continuous cropland. Zero-tension lysimeters at 105 cm depth were used to monitor drainage and leachate chemistry.

Compared with continuous cropland, grassland LE reduced nutrient leaching losses in all GCR treatments by 1-37%, depending on the nutrient. These effects were jointly regulated by LE on nutrient concentrations in leachate and on drainage quantity: LE on $NO_3$-N, $K^+$, and $SO_4$-S leaching losses was mainly controlled by concentration variations, whereas $Ca^{2+}$ and $Mg^{2+}$ losses were more closely linked to drainage intensity. Compared to a 3-year grassland phase, a 6-year grassland phase exhibited stronger legacy benefits. Nitrogen fertilization had minimal influence, and responses to successive GCR cycles varied by nutrient.

Our findings demonstrate that grassland LE play a key role in shaping nutrient leaching in GCR systems, with implications for designing effective nutrient management strategies. Extending grassland phases and using cover crops during fallow periods may reduce nutrient leaching while sustaining productivity.

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# Assessing Nutrient Status of Selected Lowland Rice Soils in Siniloan, Laguna, Philippines

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## ABSTRACT

The selected soil properties of lowland rice soils in Siniloan, Laguna, were evaluated to identify potential constraints affecting rice production. Farmers were interviewed to determine fertilizer management. Soil and plant samples were collected from 22 farms across the study site during the 2024 dry season and analyzed to determine soil texture, pH, soil organic matter (SOM), available phosphorus (P), exchangeable potassium (K), and total P and K in rice flag leaf tissue. A P adsorption test was conducted at the site with the lowest available P to describe its fixation potential. Most farmers apply P (9.86 kg P/ha) and K (18.69 kg K/ha) at suboptimal rates. In some farms, N is applied at 300 kg N/ha, exceeding the recommended rate for rice. The sites had low soil pH and acidic conditions, limiting nutrient availability. SOM was generally at a medium level, while available P ranged from 1.33 to 82.33 ppm, with some sites below deficiency thresholds and others above optimal levels, likely due to proximity to residential and lake-connected areas. The P adsorption data were fitted to the Freundlich model. The site with the lowest available P showed high fixation capacity. Most sites had exchangeable K values below the recommended levels. Plant tissue analysis revealed low total P and K concentrations in rice plants. Correlation analysis showed a significant relationship between total P, available P, and OM. These results emphasize the need for site-specific nutrient management to address potential production constraints and improve rice yields in the study area.

**Acknowledgments**

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# Synergistic Effects of Irrigation Regimes and Duckweed Species on Microplastic Dynamics in Paddy soil

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**ABSTRACT**

Rice (Oryza sativa L.) is one of the most important staple crops worldwide, and the stability of paddy ecosystems is critical for food security and environmental sustainability. In recent years, microplastics (MPs) contamination in agricultural soils and waters has become an emerging environmental concern. Microplastics can adversely affect crop growth, alter microbial community structure, and pose potential ecological and human health risks through food chains. Duckweed, a common floating aquatic plant in paddy fields, has shown strong potential for pollutant adsorption; however, its regulatory role in microplastic-contaminated paddy systems under different irrigation regimes remains poorly understood.

In this study, a controlled paddy system experiment was conducted to investigate the interactive effects of irrigation regime, duckweed species, and microplastic exposure on rice growth, microbial communities, and microplastic behavior. A three-factor experimental design was employed, including two irrigation regimes—continuous flooding (CF) and alternate wetting and drying (AWD), two duckweed species—Lemna minor and Landoltia punctata, and the presence or absence of microplastics. Rice growth performance, physiological responses, microbial community structure and functional potential, and microplastic adsorption by duckweed were systematically analyzed.

The results showed that, compared with CF, AWD irrigation exhibited distinct drying phases during the rice growth period and achieved significant water-saving effects. Under MPs stress, rice growth was markedly inhibited during the middle and late growth stages, as evidenced by significant reductions in plant height and total biomass, accompanied by decreases in chlorophyll fluorescence parameters, indicating impaired light-use efficiency and tolerance to high light intensity. Meanwhile, MPs exposure induced oxidative stress responses in rice, significantly activating the antioxidant enzyme system at the early stage of exposure.

Duckweed exhibited a strong capacity to adhere microplastics, with pronounced species-, tissue-, and hydrological-dependent differences. Landoltia punctata showed significantly higher microplastic adsorption on leaf surfaces and roots than L. minor, particularly under AWD conditions. Structural analyses indicated that the higher surface roughness and increased fold–pore structures of Landoltia punctata, especially under drying–rewetting cycles, enhanced the physical interception of microplastics. In addition, shifts in microbial communities and dissolved organic matter composition under AWD further strengthened hydrogen bonding and electrostatic interactions, contributing to the stabilization of adhered microplastics.

Overall, this study highlights the importance of integrating irrigation management and biological regulation to mitigate microplastic risks in paddy ecosystems. The combination of alternate wetting and drying irrigation with Landoltia punctata provides a promising eco-friendly strategy for enhancing paddy field sustainability under microplastic contamination scenarios.

**Keywords:** Irrigation Regimes; microplastics; AWD; Duckweed;

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# Organic slow-release nitrogen fertilizer affects soil organic carbon sequestration, greenhouse gas emission, and rice yields under water-saving irrigation

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**ABSTRACT**

Water-saving irrigation and organic slow-release nitrogen fertilizer are extensively employed in paddy fields, however, their effects on soil organic carbon sequestration (SOCS), greenhouse gas (GHG) emissions, and rice yields require further exploration, especially under aquaculture wastewater irrigation. Here, we conducted a field experiment to investigate the impacts of different irrigation regime (FSI: frequent and shallow irrigation; II: intermittent irrigation) and nitrogen fertilizer management (CK: no N fertilize; NPK: N fertilizer provided by inorganic fertilizer; SRF: N fertilizer provided by organic slow-release fertilizer) on SOCS, GHG emissions, and rice yields. Results showed that II effectively mitigated $CH_4$ emissions while concurrently increasing $CO_2$ and $N_2O$ emissions relative to FSI. Conversely, compared with NPK, SRF significantly reduced $CH_4$, $CO_2$, and $N_2O$ emissions.II significantly reduced 10.6%~13.4% $CH_4$ emission but increased 5.9%~11.3% $CO_2$ and 22.8%~27.0% $N_2O$ emission compared with FSI, and SRF significantly reduced 20.2%~21.3% $CH_4$, 10.6%~14.7% $CO_2$ and 21.3%~25.2% $N_2O$ emission compared with NPK. Compared with FSI_NPK, II_SRF significantly increased soil nutrients (TN, $NO_3$-N), rice yields by 48.7%, SOCS by 95.3%,and significantly reduced GWP by 17.2%, NGHGE by 69.5%, GHGI by 51.2%,contributing to the most mitigation of the greenhouse effect.Moreover, Soil SOC was a main predictor of $CH_4$ emission and was notably negatively related to $CH_4$ emission,while soil MBC and TN were primary predictors of rice yields and were notably positively related to rice yields.In conclusion, intermittent irrigation combined with organic slow-release nitrogen fertilizer is the optimal water and nitrogen management strategy, which can conserve water, improve rice yields, sequester carbon, and reduce greenhouse gas emissions. These findings provide valuable theoretical guidance for formulating water and fertilizer management strategies aimed at water conservation, yield increase, carbon sequestration, and emission reduction in paddy fields in China.

# Soil Science Education in Kazakhstan Universities: Strengthening Soil and Geological Literacy for Sustainable Land Management

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**ABSTRACT**

Soil is a strategic resource underpinning food production, ecosystem services, and climate regulation. In arid and semi-arid countries such as Kazakhstan, sustainable land management depends directly on the competence of soil and land-use specialists. Kazakhstan faces extensive land degradation, including erosion, salinization, desertification, and decline of soil organic matter. Similar challenges characterize Central Asia, where climate variability and irrigation-driven land transformation increase soil vulnerability.

This contribution shares Kazakhstan's experience in soil science education at the university level and reflects on recent structural changes in curricula. Reduced contact hours in soil science and geology-related disciplines have limited field practice, laboratory training, and students' engagement with soil profile description, parent material interpretation, and landscape–soil relationships. Simultaneously, decreasing emphasis on fundamental soil disciplines has narrowed academic depth in soil genesis, mineralogy, soil physics, and soil chemistry. In regions highly sensitive to salinization, wind erosion, and climate stress, soil education must develop practical diagnostic skills, critical thinking, and systems-based understanding of land processes. Strengthening soil literacy is therefore not only a disciplinary task but a strategic component of sustainable development and food security policies across Central Asia.

The presentation discusses approaches to maintaining soil science and geology as core competencies within land-related programs, including agronomy, horticulture, soil science and agrochemistry, land management, ecology, forestry, water management, and agricultural engineering. Based on current teaching practice, future-oriented directions are proposed: defining minimum learning outcomes for soil and geological literacy; preserving mandatory field and laboratory modules; integrating digital soil mapping and GIS tools into curricula; aligning with international soil classification frameworks; and reinforcing interdisciplinary links between soil science, geology, climate science, and land policy.

By sharing this experience, the contribution aims to support international dialogue on strengthening resilient and practice-oriented soil education systems.

**Keywords:** *Soil education; Soil literacy; Sustainable land management; Higher education; Central Asia*

# The World Soil of the Year: a way to promote and popularize soils

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**ABSTRACT**

In 2005, the national 'Soil of the Year' programme was initiated by the German Soil Science Society, then followed by other national societies. The successful implementation of the national World Soil Day initiatives encouraged new educational projects aimed at increasing the public awareness of soils as natural resources. In 2023, the WSY Task Force was established at the initiative of the President of IUSS, Edoardo Constantini, launching the WSY as a new project at the 100th Anniversary ofthe IUSS.

Through the World Soil of the Year (WSY), the IUSS seeks to celebrate a specific soil annually, in recognition of our collective responsibility to sustain soils and their functions, and to promote public awareness of this crucial and increasingly threatened resource. It is expected that the WSY initiative will aid in compiling a registry of soil heritage, to recognize the inherent natural and cultural values of soils, thereby helping to open doors for soil science to integrate with environmental protection activities and projects.

The World Soil of the Year (WSY) Working Group is an initiative of Division 1 of IUSSS. The WSY celebrates a special soil profile that has relevance to the environment and society. Proposals are made by national soil science societies that are members of the IUSS. The proposals must highlight the importance of soil profiles for natural or other managed ecosystem services; their uniqueness as natural features and the potential risk of their degradation and/or extinction due to natural or anthropogenic causes; their cultural relevance; and their geographic distribution. A requirement for proposals to be selected is a clear plan for outreach and communication at both the national and international levels.

The Chernozem of the Balti steppe, Moldova, was the inaugural "IUSS World Soil of the Year," presented during the closing ceremony of the 2024 Centennial Congress in Florence.

The "Gleysol - Hydromorphic soil supporting forest growth in the steppe region from the Carpathian Basin", proposed by the Hungarian Soil Science Society, was selected as WSY 2025. The representative soil profile is located at the Püspökladány Experimental Station within the Hortobágy National Park, a UNESCO Biosphere Reserve and recognized UNESCO World Heritage Site. The soil is part of a unique cultural landscape dominated by grasslands and salt-affected pastures in the Hungarian Plain.

The WSY initiative helps connect people with soils, both in the WSY country and internationally. Therefore, the chosen soil must be recognizable in similar landscapes worldwide. The focus is on communicating with people who are distant from soils in a way that is understandable to all. Emphasis is put on the use, functions, ecosystem services, and cultural and historical heritages.

# Current Status and Future Trends of Soil Education in Mongolia

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**ABSTRACT**

Soil cover plays a vital role throughout human history by ensuring food security, regulating water resources, filtering pollutants, mitigating climate change, and protecting biodiversity. Modern research defines soil as a key component of ecosystem services, and its degradation directly impacts food security, water quality, and climate stability (FAO, 2015).

In Mongolia, geography has been taught since the establishment of the first modern schools in the early 20th century, which marked the beginning of soil education within the school curriculum. Geography is taught as an integrated subject in primary education and as an independent subject in middle and high schools, with soil concepts occupying a specific place, similar to most international education systems. Currently, primary schools in Mongolia introduce basic soil concepts through the "Human and Nature"course. In grades 7 to 12, geography is taught for 1–2 hours per week (70–75 hours per academic year), of which soil-related content accounts for approximately 10–15 hours. Compared to other natural and social science subjects in secondary schools, this is twice as low. Although the proportion of soil education within geography might seem comparable to other countries at first glance, its actual content is highly deficient. This study evaluated the geography curriculum and textbooks for grades 7 to 12 of General Education Schools (GES). The analysis revealed a heavy dominance of basic knowledge, such as soil structure, properties, and distribution, whereas critical issues like soil degradation, pollution, restoration, and sustainable management are severelyunderrepresented.

Research on soil education in Mongolia remains scarce and has mostly been analyzed strictly within the scope of natural sciences. Soil topics in geography lessons are often repetitive, lack content on soil utilization and protection, and rely on overly generalized concepts of soil erosion and degradation (Davaadorj, 2024). Therefore, there is an urgent need to evaluate the current level of soil education and enrich it with content aligned with land degradation, desertification, and climate change adaptation, emphasizing the value of soil through industries, agriculture, and pasture management.

At the higher education level, the training of soil specialists is primarily centralized at the Mongolian State University of Life Sciences (MSULS). Although MSULS recruits students for agronomy-soil science programs annually, enrollment remains extremely low. This is attributed to a shortage of job opportunities and the limited hours dedicated to soil content in GES geography classes. Furthermore, while soil science is a compulsory course in the geography departments of the National University of Mongolia (NUM) and the Mongolian State University of Education (MSUE), they lack specialized soil science undergraduate programs. Although these universities offer advanced master's and doctoral programs in soil science, enrollment continues to be low. Consequently, graduate opportunities in the domestic soil sector are limited, and students increasingly pursue master's and doctoral degrees in soil science abroad.

Soil education is an integral part of environmental education and is closely aligned with the Sustainable Development Goals (SDGs). However, this study demonstrates that its scope, depth, and cognitive level within the current educational systemare insufficient.Thus, it is crucial to systematically reform curriculum and textbook contents, align them with modern educational trends, and support teacher professional development to enhance the quality of soil education in Mongolia.

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# Making Darcy visible: A simple apparatus for teaching Saturated Flow in Soil

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**ABSTRACT**

Darcy's Law relates the volumetric flow rate (Q) through a porous medium to the hydraulic conductivity (K), the cross-sectional area (A), and the hydraulic head gradient denoted by $(h_2-h_1)/L$. Owing to its wide range of practical applications, it is one of the fundamental principles taught in soil physics courses and demonstrated experimentally in undergraduate laboratories. At the first-year (100-level), students typically measure drainage rates in differently textured/structured soils using drainage tubes and a constant water head via a marotte container. While at the second-year (200-level), more advanced field methods such as the augered-hole and Guelph permeameter are introduced to determine hydraulic conductivity. Despite this, the concept of *total hydraulic head*, central to Darcy's theory, remains difficult to explain in the classroom clearly and demonstrate effectively in the laboratory.

In this study, a new teaching and experimental apparatus was developed to demonstrate Darcy's Law by varying the water head while maintaining a constant column length. Based on the Mariotte principle, the apparatus provided a simple and cost-effective means of maintaining a constant hydraulic head throughout the experiment. Using an aeolian sand with a narrow pore size distribution (50–100 μm), students determine the volumetric water flow at different head values. After graphing the results, an excellent agreement ($r^2>0.99$) was observed between hydraulic head (kept constant at 10, 20, 30, and 40 cm) and the corresponding Darcy flow rates. The estimated hydraulic conductivity was then used to predict the flow rate at a 50 cm head, which closely matched the measured value, thereby validating the approach.
Overall, this apparatus offers a cost-effective, practical and visually intuitive tool for enhancing undergraduate understanding of saturated flow dynamics and the role of hydraulic head in governing water movement through soils.

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# Deciphering Soils through the Power of Games

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**ABSTRACT**

In university level soil science education, many concepts lack equivalents in students' everyday knowledge. Terms such as calicata, or Luvisol (LV) may seem unfamiliar or even intimidating to those approaching soil studies for the first time. At the bachelor's degree in Geohistory at the National Autonomous University of Mexico (UNAM), campus Morelia, we have incorporated the telepictionary technique as a playful and collaborative tool to facilitate the understanding of soil science concepts.

Over three generations of students, this game has allowed young learners to transform unknown terms into their own drawings, creating visual and narrative associations that strengthen their analytical thinking and conceptual memory. Through images, participants reinterpret the technical language of soil science from their own perspectives and context, successfully integrating its basic principles.

The results show that learning mediated through play not only sparks creativity, curiosity and enjoyment, but also fosters a deeper appropriation of knowledge. When classifying soils, students recall the images created collectively, turning a complex task into a meaningful experience. This approach demonstrates that play can serve as a bridge between imagination and science, between the soils and those who study it.

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# The Virtual Soil Museum of Northern Paraná: A Space for Soil Education

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**ABSTRACT**

Soil Education in Brazil manifests itself across multiple educational spaces, both formal and non-formal, with purposes ranging from teaching and outreach to the popularization of science (Silva, Vezzani & Lima, 2022). Various fields of knowledge and learning environments can be mobilized in this process, such as virtual museums. Science museums have become consolidated as spaces of non-formal education, fostering dialogue between science and society and contributing to Soil Education. In this regard**,** Pedron et al. (2022) point out that soil education in museums is a continuous process of knowledge production that begins with the conception of collections, continues through their study, is expressed in the form of exhibitions, develops pedagogical practices, and involves the analysis of educational and scientific activities through interaction with the public. Within this context, this study aims to present the Virtual Soil Museum of Northern Paraná (MUVISOLOS)**,** highlighting it as a virtual environment dedicated to scientific dissemination and the appreciation of pedological heritage. According to Henriques (2018)**,** virtual museums are characterized as collections of digital records — images, texts, audio files, and other data of scientific, historical, or cultural interest — accessed through electronic media. They are defined as institutions without a physical location but with an interactive presence in virtual space. The MUVISOLOS (https://muvisolo.wixsite.com/museu-de-solos-norte) is linked to the Geography degree program at the State University of Northern Paraná, and was created in 2024 with the purpose of providing, in a virtual environment, information about the soils of the 125 municipalities of Northern Paraná. The museum seeks to promote understanding of the region's pedological heritage and to foster awareness regarding the sustainable use and conservation of soils.

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# From Soil Pits to Global Goals: Reimagining Soil Education for a Sustainable Future

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## ABSTRACT

Soil science stands at a crossroads. Despite its key role in food security, water, climate, biodiversity, and the SDGs, its teaching remains narrow. This work calls for a transformative curriculum uniting science, sustainability, and social engagement. Using examples from Sultan Qaboos University (SQU) (Oman) and Moscow State University (Russia), and insights from Europe (Veenstra et al., 2024), this study shows how inquiry-based learning, SDG-focused teaching, and community projects build skills in systems thinking, ethics, and problem-solving. At Sultan Qaboos University (Oman), the BSc in Soil Sciences was restructured as a whole-program reform anchored in graduate attributes and aligned with the SDGs. Outcomes linked soil functions to ecosystem services in arid settings. The SQU model, unlike piecemeal course updates, ensures coherence and progressive learning, echoing Spronken-Smith et al. (2011) that holistic design builds enduring competencies - a sustainability imperative. To unlock soil education's transformative potential, key strategic actions are recommended: (1) Link soil functions to ecosystem services and sustainability outcomes to integrate the SDGs; (2) Institutionalize interdisciplinary collaboration across engineering, economics, and policy; (3) Expand student-led research, living laboratories, and stakeholder partnerships to enhance experiential learning; (4) Integrate emerging technologies such as modeling, machine learning, and data analytics to advance soil understanding, prediction, and decision-making, and (5) Invest in faculty development, global mobility, and impact evaluation to sustain educational innovation. Soil education is thus re-designed, moving beyond technical training to become a catalyst for sustainability - inspiring curiosity, responsibility, and action. Embedding soil in SDG policies and education is vital stimulate future generations to see soil as the living foundation of life.

**Keywords:** Soil education, Ecosystem services, Inquiry-based learning, Soil Skills, transformative pedagogy

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# SUSTAINABLE LAND MANAGEMENT STUDY IN TERTIARY INSTITUTIONS FOR LAND RECLAMATION: KEY TO SUSTAINABLE AGRICULTURE

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**ABSTRACT**

Land contamination/pollution reduces the carrying capacity of the land and its ability to meet the food demand of the ever-growing population thereby posing threats to food safety and security. Education on sustainable methods for managing soil resources and restoration of polluted soils through research is pertinent for increasing agricultural production and promoting food security. SLM approach refers to the use of one or several SLM Technologies. Study was carried out on the integrated use of environmentally friendly and cost-effective methods like bioremediation and phytoremediation for managing contaminated soils. The phytoremediation potential of *Leuceana leucocephala* on the heavy metal and crude oil polluted soils amended with compost and biochar. The heavy metal contaminated soil was collected from the lead acid battery waste dumpsite that was first mixed with uncontaminated soil to give a 50% level of contamination before the addition of compost and biochar. Uncontaminated soil was also spiked with crude oil at 5% of the soil weight measured at 500 grams/cup. Biochar and compost were applied at the rates of 0, 2.5, 5,10 tons/ha (0-Control, 2.5t/ha-C1, 5t/ha-C2, 10t/ha-C3, 2.5t/ha-B1, 5t/ha-B2, 10t/ha-B3) while control treatment served as check. Seeds of *Leuceana leucocephala* were first subjected to $H_2SO4$ treatment to break the dormancy before planting at 7 days after soil amendments with compost and biochar. Data were collected on growth, proline, phenolics, heavy metal uptake, biomass and post-cropping metal analysis. Results showed that heavy metal contamination and oil pollution affected the growth of *L. leucocephala*. However, application of compost and biochar, especially their combination, gave the highest number of leaves, plant height and biomass accumulation in *Leuceana leucocephala*. The proline and total phenolic contents of the plants grown in the heavy metal-polluted soil (unamended) were the highest compared to those treated with organic amendment. This indicated the ability of the amendments in reducing stress on the phytoremediator while enhancing metal uptake. Plants grown in the soil without amendments had the highest concentrations of these metabolites which enhanced the tolerance of these plants in contaminated soils. Results of post-cropping soil analysis however, showed increase in soil lead content with C2. This shows that application of organic amendments enhanced plant growth but also immobilized metal for uptake by phytoremediator. In conclusion, *Leuceana leucocephala* was able to grow on heavy metal and crude oil polluted soils amended with compost and biochar and produced higher amounts of proline and phenolics, for tolerance in the polluted soils. The use of organic amendments in combination with phytoremediation technology could be promoted for sustainable soil management and can be included in the soil management curriculum.

**Keywords:** Soil contamination, Heavy metal, Biochar, Compost, Crude Oil, Sustainanbility

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# Experiential learning in the field: assessing the impact of the 2024 Moana Oceania Soil Judging Competition (New Zealand) on participants knowledge, skills and attitudes.

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## ABSTRACT

As soil science educators we need to rebuild communities of knowledge and train work ready graduates. There is not only a lack of graduates with field-based soil skills, but there is also a disconnect between soils and landscapes. Graduates often have limited field descriptive and interpretation skills. Students like learning in the field; it helps them to comprehend soils as not only part of the biophysical and cultural landscape but also as part of a functioning ecosystem. In the field, there is more time to think and to interact with teaching staff so that learning occurs at a deeper level. But we are increasingly offering less opportunities to do this in tertiary institutions, even though we know intuitively that learning in the field is highly effective, as it is a pedagogically aligned approach.

Soil judging competitions (SJC) provide an experiential approach to teaching and learning essential skills in soil science. SJC are designed to upskill participants in the ability to accurately describe soil profiles and make land use interpretation decisions, compared to an expert description/ interpretation. These competitions have been run in Australia since 2012 and in New Zealand since 2016.

In 2024, the Moana Oceania Soil Judging Competition (MOSJC) was hosted in New Zealand, as part of the joint conference of the New Zealand Society of Soil Science and Soil Science Australia. This SJC involved over 200 participants and 35 teams from 9 countries in the South Pacific region: including 80 students and 70 working professionals. This study aimed to determine the impact of the MOSJC on participants' learning of soil-related knowledge and skills and on their attitudes towards soil science. Participants were asked to complete voluntary pre- and post-competition surveys covering demographic information and self-reported understanding and ability.

Ninety-eight participants completed the pre-contest survey and 56 completed the post-contest survey. Results showed an increase in participants' self-reported skill and knowledge of understanding soil judging characteristics (e.g. soil morphology and site interpretation). Most participants had positive attitudes towards soil science and soil judging, with no significant change due to the competition. Self-reported responses about desired gains from the competition included networking (30%), technical skills (25%), knowledge building (20%), regional knowledge (15%), and professional development (10%).

The wider contribution of soil judging to society is built around increasing how we connect to the soil. If we can support people to have relevant soil knowledge and a deep understanding of the soil within the planet ecosystem, we can strive for soil security and a sustainable future. To achieve this, education is key to building enduring connections to soil.

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# EXPLORING THE SOIL: Learning and service guide to assess soil quality

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**ABSTRACT**

The **European Soil Strategy 2030** warns of a widespread lack of knowledge about soil in European educational curricula. The main shortcomings identified are: the very limited inclusion of soil health in compulsory content, especially at the early educational stages; a fragmented and disconnected treatment of soil in relation to key areas such as biodiversity, climate change, and food security; and a shortage of teaching resources and practical activities that enable soil to be addressed as an essential resource for sustainability.

This context reinforces the need to promote **innovative educational initiatives** that integrate soil health into the curriculum and encourage active student participation. The guide **Exploring the Soil**, promoted by the Government of Catalonia with the support of European funds and designed by CREAF-UAB and UdL, aims to **raise students' awareness and foster their commitment** to improving soil quality in nearby environments, such as school grounds and municipal spaces.

The methodology combines two educational strategies: **Service-Learning (ApS)**, which integrates curricular learning with real community service, connecting knowledge with action; and **Citizen Science**, which involves the active participation of non-experts—in this case, students—in scientific processes to generate data and knowledge useful to society.

The structure of the guide provides a sequence of sessions adaptable to the organization and possibilities of each educational center, including: introductory sessions that provide context and knowledge about soil and its current challenges; practical field and laboratory sessions to analyze indicators based on physical, chemical, and biological soil properties; and the preparation of a synthesis document (scientific article, poster, or report) summarizing the results, which is presented at a final institutional recognition event attended by local administrations or interested research centers. The initiative promotes **applied scientific knowledge, environmental awareness, and transformative action**, contributing to sustainable land management and the fight against the climate emergency.

During late 2025 and throughout 2026, a **pilot test** will be carried out in which several secondary schools will implement this project under the guidance of the authors. The purpose of this presentation is to introduce the project and its conceptual and methodological characteristics, as well as to present the first results of soil quality assessments conducted by Catalan secondary school students.

**Acknowledgments**

Department of Education, Government of Catalonia; RIS3CAT 2030 Strategy

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# Digging Deeper into the State of Collegiate Soil Judging in the United States

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**ABSTRACT**

Collegiate soil judging is an academic competition where students analyze soil profiles and interpret land usage. However, despite its educational benefits, the costs associated with travel, lodging, and competition fees can be prohibitive, especially for teams from smaller or less-funded institutions. This lack of financial support not only limits students' opportunities to engage in these enriching experiences but also creates disparities in access to professional development and networking opportunities within the field of soil science. The objective of this study was to identify the key financial challenges faced by these teams and provide baseline demographic information for soil judging teams in the United States. We surveyed 50 current head coaches of soil judging programs in the United States to understand team funding, student participation, and obstacles to sustaining a successful program. We found that coaches consistently identified limited time and funding as the most limiting factors to maintaining a soil judging program. Despite dedicating an average of 3-6 hours per week to recruitment, training, and travel, most coaches receive no formal compensation. Financial constraints not only place the burden of fundraising predominantly on coaches but also limit student participation. Our survey showed that one in four soil judging teams reported limiting the number of students who traveled to a contest due to financial limitations, and over half required students to cover part of their own expenses. Moreover, most teams cannot attend two contests per year unless the contest is nearby geographically, or if they spend significant time and effort fundraising, which further exacerbates the issues with coaches' time and compensation. The skills learned from soil judging are critical for the next generation of successful soil scientists, and when programs are under-resourced, students miss out on these transformative opportunities. Addressing these challenges is essential to adequately support coaches for their invaluable contributions and ensure that students can develop critical skills and engage in opportunities necessary for success in soil science.

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# Building Soil Science Literacy: Assessing Impact in K-12 Teacher Training

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**ABSTRACT**

The Soil Science Society of America (SSSA) K-12 Teacher Outreach Committee created a one-day in-service program to provide ready-to-use, hands-on training in soil science for middle (grades 6-8) and high school (grades 9-12) educators. This initiative addresses the gap in soil science education: while the Next Generation Science Standards (NGSS) form the basis for new science standards across the United States, soil is not specifically included in the disciplinary core ideas, leading to less classroom focus. The program we developed aims to build teacher competency, confidence, and comfort using SSSA-developed, modular teaching materials. The committee has successfully conducted six in-service events, created web resources, and translated materials into Spanish. This presentation will outline the program, share assessment data from workshop participants, and propose a model for other scientific societies to implement similar outreach.

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# Enhancing Soil Science Laboratory Learning through a Computer-Based Mineral Identification Program (MIP)

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## ABSTRACT

Laboratory instruction in mineral identification involves multiple diagnostic steps, which can be challenging for undergraduate learners. Integrating computer-based technology into teaching may enhance instructional effectiveness for students in the digital era. This study aimed to evaluate the effectiveness of using the Mineral Identification Program (MIP) in a soil science laboratory course for undergraduate students in agriculture. The participants were 39 second-year students in a Bachelor of Science (Agriculture) program. Descriptive statistics were used to assess students' perceptions of the new instructional method. Most students had GPA between 2.00–2.49 and 2.50–2.99, and nearly all had no prior experience in mineral identification. The findings indicated that students held highly positive attitudes toward the new teaching approach. More than 80% of respondents selected levels 4 and 5 ("agree" or "strongly agree") on all items related to correctly, ease of learning, and satisfaction. In terms of learning outcomes, post-test scores were significantly higher than pre-test scores at P value< 0.000. These results suggest that the MIP-based instructional approach was well received and effectively enhanced students' learning performance. Continued development of innovative, active-learning approaches is recommended to support the achievement of learning outcomes in future courses.

**Keywords:** Laboratory Learning, Soil Science, Mineral Identification Program, Learning Outcomes

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# Fostering Soil Science: Insights from the 1st European Soil Judging Contest

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**ABSTRACT**

Soil Judging Contests serve as a practical and formative approach to soil science, offering students an engaging opportunity to describe, interpret, and classify soils in the field. The 1st European Soil Judging Contest, organized by the Soil Science Department of the University Miguel Hernández (Spain) with the assistance of Environmental Sciences students, was held in Alcoi, Alicante, Spain, from 1-5 September 2025. The event brought together teams from eight participating countries: France, Germany, Hungary, Italy, Latvia, Poland, Portugal, and Spain.

This kind of contest aims to foster a European network for field-based learning and promote collaboration among universities and young scientists. Each national team comprises four members—either undergraduate, master's, or doctoral students—alongside one or two coaches. The competition features an intensive four-day program that includes classroom instruction, field simulations, and two days dedicated to the competition. Participants utilize a comprehensive field manual that outlines soil descriptions according to the two main global classification systems in the last versions: Soil Taxonomy and the World References Base for Soil Resources.

The competition format includes two profiles for team contest and two for individual part. Teams are tasked with describing a designated soil profile within one hour, focusing on the characteristics of various soil horizons and subsequently classifying the soils based on the collected data. Evaluation is conducted by filling out specific forms for each soil profile, with points awarded for each data entry, culminating in a total score that determines the competition winner.

Pre-competition and post-competition online sessions facilitated logistical explanations and collected participant feedback. Competitors expressed positive experiences regarding the educational aspects and motivation to further engage in soil sciences and scientific outreach initiatives.

The educational value of these contests is significant; they promote active learning, critical observation, and practical skills in soil description and classification. Moreover, they encourage teamwork and problem-solving abilities while contributing to the scientific dissemination of soil science. Therefore, this event not only highlights the importance of practical soil science education but also strengthens the connections among future soil scientists across Europe.

More detailed information and the materials used can be found on the website: https://esjc.es/

**Acknowledgments**

We thank the scientific committee of the contest, participants, to all our Sponsors, BIP Erasmus+ funding program, IUSS, SECS, and Generalitat Valenciana for their invaluable contribution to the success of the 1st European Soil Judging Contest.

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# Co-developing soil science teaching and learning across North-South – a unique educational collaboration between The University of Melbourne and National University of Laos

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**ABSTRACT**

This presentation describes a novel, exemplar cross-country university collaboration in soil science education involving co-design of curriculum and pedagogy. As one of the four key work packages (WP4) of the Australian Centre of International Agricultural Research (ACIAR) project *Quantifying the impacts of nitrogen use and developing sustainable agricultural nitrogen management strategies in Laos rice-based farming systems* (2022/102) (ACIAR 2025), University of Melbourne (UoM) has been collaborating closely with the National University of Laos (NUoL) on the curriculum design and development, official approval, and incipient delivery of the new Bachelor of Science in Sustainable Agricultural Land Management (BSc SALAM), where soil science is a core component of the degree. The BSc SALAM is designed to educate the next generation of leading soil scientists, agronomists, land resource managers, agribusiness professionals and agri-entreprenuers. It is also one of the key pillars for the present ACIAR project, in strategic capacity-building of indigenous soil and crop analytical and advisory capabilities in Laos PDR.

The pedagogical design of soil science learning by UoM-NUoL will be based on the 11 Soil Science teaching principles (Field et al., 2011), inspired by the joy and fascination of soil science and discipline-adjacent practitioners and educators (Hartemink et al. 2014), and determined to make long-term impacts on farming practices, natural resource management and environmental sustainability of Lao PDR in meeting national strategic objectives and the UN Sustainable Development Goals (UN SDGs) 4,5,15-17.

This collaboration while still underway, has seen mutual exchanges of knowledge about soil science and teaching that stems from deeper understanding of the distinct agro-ecological, climatic and pedological contexts between Australia and Laos. As part of the project, existing links and resource sharing between NUoL, the Department of Land Management (DLAM), National Agriculture and Forestry Research Institute (NAFRI), and regional/provincial agricultural offices are being strengthened and leveraged upon.

To illustrate this dynamic collaboration, this presentation will describe how the content of soil science subjects in BSc SALAM will be delivered through authentic learning techniques aligned with Field et al. (2011). This includes clearly linking soil science principles and practices to the spectrum of agricultural production systems in Laos and Australia, environmental sustainability concerns such as greenhouse gas emissions, fertilizer use, and practical skills in the laboratory and field.

**Acknowledgments**

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# Building Soil Literacy Through LADA: Teaching Soil Assessment, SOC Understanding, and Reliable Sampling

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## ABSTRACT

Strengthening soil literacy is critical in regions experiencing rapid land degradation and limited soil data, such as Kazakhstan. The LADA (Land Degradation Assessment in Drylands) methodology provides an effective educational framework that links visual soil diagnostics, organic carbon understanding, and standardized sampling practices. Teaching LADA-based indicators—structure, salinity, compaction, vegetation cover, and erosion—enables students, farmers, and civil society to rapidly interpret soil condition, even in data-sparse landscapes.

Organic carbon literacy is especially important. Kazakhstan currently relies on sparse public datasets (only 52 ISRIC samples nationally) and various AI-based soil predictions that remain unreliable without dense field sampling. By integrating LADA field observations with SOC concepts, learners better understand carbon formation, loss pathways, and the risks associated with incorrect baselines. Practical exercises illustrate how sampling depth, land-use history, moisture, and salinity influence SOC variability and the accuracy of carbon-credit calculations.

A key component of soil-literacy education is training in reliable sample collections. Learners follow standardized procedures for composite sampling, depth separation (0–30/30–60 cm), contamination control, labeling, and GPS documentation. These skills help overcome the baseline inconsistencies commonly found in national soil assessments and reduce uncertainties in future soil databases.

Experience from university teaching, research field schools, and digital soil-monitoring activities demonstrates that combining LADA diagnostics, SOC education, and proper sampling significantly improves practical competence. This integrated approach prepares students, young researchers, and community participants to critically evaluate AI-generated predictions, contribute to local carbon-monitoring initiatives, and support the development of a unified national soil-information system. Such capacity is essential for sustainable agriculture, climate-resilient land management, and long-term environmental stewardship.

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# An International Master school in Applied Soil Science. The EU project "Medsoils-challenge"

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**ABSTRACT**

The Mediterranean region is one of the most susceptible regions for soil degradation and desertification and is considered a climate change "hotspot". A new generation of soil experts equipped with interdisciplinary training, skills and integrated approaches is needed to develop and implement innovative, sustainable, and long-term solutions for soils and related ecosystem services.

In 2024, the Medsoils-Challenge project was funded by the European Union Erasmus+ program "Cooperation Partnerships in Higher Education", to develop a pilot Joint Master's degree in "Applied Soil Science for Mediterranean Areas" (https://medsoil-challenge.eu/).

The project involves four universities and two technical partners from four Mediterranean countries (Italy, Spain, Slovenia, and Türkiye) in the design and piloting of an annual Master's course. The project includes:

- in-depth analysis of training needs and skills mapping, involving experts and stakeholders;
- scientific and administrative design and signing of the Master's program, including its content and tools;
- development of a pilot annual Master's degree, involving students selected by the four universities.

The Master's course is planned in a blended mode, featuring online lectures and exercises, as well as four intensive weeks, one in each participating country, with face-to-face activities, field excursions and practical exercises. This will be followed by a two-month internship in a company or research center and a final thesis, completing the educational path. Sixteen scholarships, covering all student expenses including mobility during face-to-face activities, are covered by the project funds. This dynamic Master's program will feature instructors from various disciplines relevant to soil science, alongside academics in the field, empowering students with the knowledge needed to address future challenges.

The course will be divided into four modules:

1) Soil survey and classification: including field survey and mapping methodologies, identification of pedofeatures, WRB and Soil Taxonomy classification
2) Soil quality monitoring: introducing the main methodologies for monitoring indicators of soil quality and health
3) Technology supporting soil survey and monitoring: including proximal soil sensing, introduction to remote sensing, digital soil mapping and decision support systems
4) Applications of soil science: including urban and rural development planning, land evaluation, soil conservation and recovery, participatory processes, and carbon farming.

The course will begin in September 2026 and conclude in September 2027 with the thesis defense.

**Acknowledgments**

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# Sculpting the Campus, Cultivating Soil: An Eco-Art Pedagogy of Care and Action

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**ABSTRACT**

This proposal presents the "Healing Garden" as a replicable eco-art pedagogical model for innovative soil education,inspired by the integrative "soil-soul-society" paradigm. It uniquely integrates eco-art, eco-pedagogy, and constructive activism under the ethical and design framework of permaculture. We reposition the university campus as a "social sculpture"—a living material reshaped through direct, care-driven actions to foster new human-soil relationships. Our model's distinctiveness lies in three interwoven strands: (1) Permaculture as Foundational Design Language, transforming marginalized spaces into learning commons and valuing local knowledge-holders; (2) Eco-Art as Embodied Learning Methodology, where soil literacy is cultivated through sensorial co-creation (e.g., Mandala Gardens, soil paintings with compost pigment, ecological dry toilets as public sculpture); and (3) "Inviting-In" as Constructive Campus Activism, curating the campus as a site for engaged, co-learning communities. The student-managed composting system—diverting 28.42 tons of kitchen waste—demonstrates scalable ecological repair and enhanced student agency. This model offers a framework for "soil education as social-ecological practice," transforming institutions into nodes of resilience, bioregional care, and participatory learning.

**Keywords:** Eco-Art, Permaculture, Constructive Activism, Social Sculpture, Campus Ecology

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# Cultivating Soil Literacy in China: Assessing the Soil Collage as a Transformative Educational Tool

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**ABSTRACT**

Background: Soil literacy is regarded as the comprehensive understanding of soil as a living, dynamic ecosystem that sustains life on earth, the appreciation of its vital role in supporting our planet and human society, and the practices that contribute to soil health. The pervasive "soil blindness" in modern society underscores a critical gap in soil science education, from schools to civil society. To bridge this gap, we introduced "La Fresque du Sol" (the Soil Collage), an innovative educational tool co-designed by 38 soil scientists in France by ADEME (French National Agency for Ecological Transition) andAFES (French Soil Science Society). As a 3-hour participatory design workshop where participants use scientific cards and collective intelligence to reconstruct the puzzle of soil ecosystem, this tool moves beyond traditional pedagogy and adopts engaging, interactive methods that make the complex, hidden world of soil tangible and relevant.

Research Question: To what extent does the soil collage contribute to enhancing soil literacy of the general public?

Method: We have conducted pre-workshop survey and post-workshop semi-structured interviews among 16 urban residents aged 22-55 in Eastern China, including community gardeners, college students, company employees, and nature lovers.

Results and Discussion: Preliminary assessment of survey data and qualitative analysis of interview data reveal significant shifts in participants' soil literacy across three dimensions:

• Cognitive: A marked increase in understanding of soil as a living, complex ecosystem and its nexus with climate and water systems.

• Affective: A strong emergence of emotional connection and appreciation of soil, awareness of soil artificialization, concern for soil degradation, and a sense of responsibility.

• Behavioral: A demonstrated increase in intention to adopt soil-friendly practices (e.g., composting, informed consumption) and engage in community advocacy (e.g., planning a forest garden/food forest).

Conclusion: La Fresque du Sol transcends the conventional definition of an educational game by offering an innovative blend of engagement, thought-provoking and participatory design. It fosters collaborative knowledge construction and facilitates deep emotional resonance among participants. More than just a learning tool, it serves as a powerful and scalable pedagogical intervention that effectively translates ABSTRACT soil science concepts into a compelling narrative of human-soil interconnectedness. Our findings advocate for integrating such experiential and participatory approaches into the future of soil science education worldwide—from formal curricula to lifelong learning platforms—to cultivate a soil-literate global citizenry essential for a sustainable planet.

**Acknowledgments**

We would like to extend our sincere gratitude to the developers of La Fresque du Sol, namely Antoine Pierart and his colleagues atADEME whose groundbreaking approach to soil education served as the foundation for this presentation. Our appreciation also goes to Paris2050 Workshop for fostering an environment of collaborative learning and interdisciplinary dialogue. Their commitment to translating complex soil science into an engaging and accessible format is a testament to the power of collective intelligence.

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# Soil: Eternal Heritage and Khayyam's Perspective

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**ABSTRACT**

Soil, a silent yet life-sustaining foundation, is one of the most fundamental elements for the continuity of human life and ecosystems. Today, soil erosion and pollution have become among the most critical environmental challenges, highlighting the urgent need to reconsider the human-nature relationship. Protecting soil is not merely an environmental issue but also a cultural and ethical responsibility, which can be reinforced by drawing on the literary and intellectual heritage of great thinkers.

Omar Khayyam, the renowned Persian poet and philosopher, frequently addressed soil in his quatrains, placing it at the center of his philosophical and poetic reflections. In one notable quatrain, he writes:

*"Every blade of grass that grows beside a stream*
*Seems to have sprung from the lips of an angel.*
*Do not trample the grass to shame it,*
*For it has risen from the soil that nurtures the tulip."*

This verse elegantly captures Khayyam's view that life and beauty emerge from the soil, and that all living beings, even a simple blade of grass, merit respect. The grass, as a metaphor, reflects both the fragility and sanctity of life, while the soil symbolizes the ultimate source and return of existence. By drawing attention to the origin of life in the soil, Khayyam conveys an ethical as well as mystical message: the impermanence of worldly forms and the unity of human fate. In Khayyam's thought, soil is both the origin and the ultimate destination of human beings, embodying the cycle of birth, decay, and return. Although not expressed in conventional Sufi terminology, his view resonates with mystical concepts such as annihilation, permanence, and return to the origin. Combining philosophical reasoning with poetic intuition, he presents soil as a mirror for comprehending the truth of existence, where death is not an absolute end but a stage within the cyclical process of being. From a scientific standpoint, soil is also the product of a slow and gradual process; forming just one centimeter of soil may take hundreds to thousands of years. This fact renders soil an intergenerational legacy, whose destruction can lead to irreparable consequences. Linking this scientific reality with Khayyam's symbolic view offers a fresh interpretation of his quatrains, presenting soil not only as a philosophical and poetic subject but also as a vital resource for humanity's future. Poetry has the power to translate scientific concepts and environmental warnings into the language of human emotion and thought. When Khayyam speaks of soil, he invites the audience to reflect on its value and humanity's responsibility toward it. In this context, Khayyam's thought, beyond its literary and philosophical significance, has the potential to play an enlightening and ethical role in contemporary environmental discourse. Protecting soil, in this reading, is tantamount to safeguarding life and the future of humanity.

**Keywords:** Omar Khayyam, Soil as a Symbol, Mystical Thought, Life and Decay, Philosophical Reflection,

Environmental Awareness

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# Asking once more; What is the essential knowledge of soil in early education, particularly in Monsoon Asian countries?

**ABSTRACT**

Soil is an essential resource for our life and soil education is an important task worldwide. However, soil may be taken for granted in Monsoon Asian countries. This area comprises only 18% of the world cultivated area while it produces 33% of world GDP and supports 48% of world population. This is at least partly due to high rice yield with paddy filed production system. People in these countries may not fully recognize such benefit. On the other hand, soil degradation and decrease in productivity may also slowly occur in these countries. At the same time, many world conflicts and environmental issues are becoming closer between physically distanced countries due to enlarging scale of problems and extensive transportation network worldwide. Soil is one of the important key to solve the“crisis”, and teaching soil is an urgent issue all over the world. So, we ask once more, what should be taught about soil in early education? Is there any topic particularly of Monsoon Asian countries to draw more attention to soil?

Understanding soil through its function is valid. Soil as a base for natural and planted vegetation, and providing food for us may come in the center of the soil function. Other important functions are providing space for diverse soil organisms, decomposition of organic matter, serving as pool for organic matter, playing fundamental role in the quality and availability of terrestrial water. In early education, firstly, feeling and becoming familiar with soil and recognize soil as a part of the natural environment is very important. Then basic knowledge of soil which leads to understanding above soil function is necessary.

To learn about soil in Monsoon Asian countries including Japan, rice production systems could be a good tool, and we suggest learning about comprehensive rice production systems. By learning such, pupils can learn where soil materials come from which link to river water function and landform, soil characteristic, climate, civil engineering systems of irrigation canal, and benefit we obtain from such production system, in addition to some of the above soil function. Such study not only covers science but also social studies. We will present an example of a field workshop for primary school students and their parents about rice production and soil (Hirai and Mori, 2020). They did soil surveys on differently treated rice fields and surrounding environment, calculated number of stalk clump and wet soil for one portion of rice. Through such workshop, participants can understand the relationship between forest, soil, water, paddy field, rice and their life.

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# Comprehensive Soil Education Package for Achieving SDGs: Good practices in schools and universities

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**ABSTRACT**

There is no doubt that soil education is an urgent issue to achieve SDGs by 2030. In spite of its importance soil may be neither taught effectively in educational sector nor understood comprehensively in civil society in many countries, allowing soil and land degradation to lead us to face a variety of global environmental challenges. The objective of this research is to develop a comprehensive soil education package, particularly for achieving SDGs, to be applicable to those from pre-school children to the general public in as well as out of doors.

The contents of the package include the topics for stimulating the sense of wonder, for providing basic knowledge of soil forming processes and its distribution pattern to understand the principles of soil and land use management, nutrient cycling in an ecosystem and various aspect of ecosystem services, and for facilitating practical observation and experiments in a field and/or laboratories. In each topic the contents are arranged in problem-finding-solving style, i.e., observing the current status of nature, objects or problems first, then raising the question why it is so, and discussing among the learners and finally finding the answer or solution.

Here will be presented three topics developed and modified for the elementary school children and high school and university students: 1) soil nutrient regulating plant growth, 2) soil-related research competition, and 3) training course for pedology. The first topic is developed and recommended for the 6th grade children in the elementary school. They are to learn the role of nutrient held, exchanged and served by soils for plant growth by comparing water-extract of soils with tap water. The second has been conducted and managed by the Japanese Society of Soil Science and Plant Nutrition since 2009, being participated by about 30 high school teams from all over the country in 2025. Most of their research are highly motivated and self-driven, partially guided by supervisors such as school teachers and/or the members of the society. The third was started in 1989 by the Japanese Society of Pedology so as to train the undergraduate and graduate students in describing, classifying and evaluating soils in the field. Forty to fifty, sometimes more, students are participated every year and the contents well complement the course work of Soil Science and related subjects provided in the class rooms and labs in the university. This training course is now in the upgrading process to meet the level required for joining a variety of international soil judging contest/competitions frequently conducted nowadays in different locations/ecosystems in the world. The questionnaire survey and/or participation observation proved they work efficiently in stimulating sense of wonder, enhancing intellectual curiosity and improving the skill of analyzing as well as integrating the information of soils and soil sciences for achieving SDGs.

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# Pedagogical Fossilization in the Era ofAI: The Risks of Algorithmic Bias in Soil Science Education

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**ABSTRACT**

As Artificial Intelligence (AI) and Large Language Models (LLMs) increasingly function as informal tutors for university students and professionals in civil society, they reshape how Soil Science is learned. While these tools promise to democratize access to technical knowledge, we hypothesize that they inherently suffer from "Algorithmic Pedagogical Fossilization," a phenomenon where AI reinforces historical paradigms at the expense of modern, robust methodologies.

This study aims to investigate this bias using Geostatistics and Digital Soil Mapping as a pedagogical case study. We posit that current LLMs are influenced by three distinct biases: (1) Representation Bias, caused by the predominance of historical literature (e.g., classical Method of Moments) in training data compared to newer, less voluminous literature (e.g., Model-Based Geostatistics/REML); (2) Frequency Bias, where statistical word associations favor traditional terminology; and (3) Simplification Bias, where the model's alignment for user satisfaction prioritizes intuitive, visual explanations (such as experimental variograms) over complex, ABSTRACT concepts (such as likelihood functions).

We will present a systematic evaluation of major Generative AI models when prompted to explain and generate code for spatial interpolation tasks. We anticipate demonstrating that, without expert mediation, these "digital tutors" fail to provide the necessary pedagogical scaffolding to lead learners from simple concepts to rigorous uncertainty quantification. Consequently, uncritical adoption of AI in soil education risks creating an "illusion of competence," where students can execute tasks using obsolete workflows without understanding their statistical limitations. We conclude by discussing the urgent need to integrate "AI Literacy" into the soil science curriculum to ensure future professionals can critically interrogate, rather than passively consume, algorithmic guidance.

**Keywords:** Artificial Intelligence, Soil Education, Geostatistics, Algorithmic Bias, AI Literacy.

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# A Study on the Educational Value and Innovative Mechanism of the "Freshmen's Cup of Hometown Soil" Practical Teaching Model

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**ABSTRACT**

Against the backdrop of the reform of agricultural education and the Rural Revitalization Strategy in the New Era, how to organically integrate professional cognitive education, practical teaching, and serving the "Three Rural Issues" has become an important question that higher agricultural colleges and universities need to urgently address. Since 2021, the College of Resources and Environment, Xinjiang Agricultural University, has continuously carried out the "Freshmen's Cup of Hometown Soil" social practice activity, which guides freshmen to collect soil samples from their hometowns before enrollment, complete systematic analysis, application and feedback after enrollment, and has constructed a continuous practical teaching model of "Touching Soil-Understanding Soil-Improving Soil-Utilizing Soil". Based on the implementation process and phased results of this activity, this paper systematically sorts out and summarizes the "Freshmen's Cup of Hometown Soil" practical model from the aspects of innovation in practical teaching, students' professional identity, synergy between scientific research and talent cultivation, and paths of achievement transformation. The study holds that this model has effectively expanded the temporal and spatial boundaries of practical teaching for agricultural majors, strengthened students' understanding and emotional identification with soil science and modern agriculture, and at the same time provided practical support for the construction of regional soil big data and green agricultural development, which has important References significance for the innovation of practical teaching models in higher agricultural education in the context of New Agricultural Sciences.

**Key words:** New Agriculture Disciplines; Practical Teaching; Soil Science; Professional Identity; Rural Revitalization

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# It's the pits! Cementing theory through practice in soil science teaching

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**ABSTRACT**

Week 1 of soil science teaching at the University of Aberdeen takes students armed only with spades, a measuring tape, a Munsell colour chart and a sampling sheet to dig a soil pit and describe the profile using FitzPatrick's Soil Description book. They work in groups of 4-5, gelling as a cohort in mutual despair of the complex task ahead. Over the next few hours, soil scientists are born. Starting with little knowledge, each group describes their profile and the surrounding environment, and they consider how the soils are formed and used. Students leave with some knowledge of 3 RSGs and an eagerness to learn more. This practical introduction to soil is not just about surveying – it underpins our in-class teaching as concepts ranging from soil formation to the finer points of soil physics are now easier for students to grasp and appreciate. Every week another field practical builds on the last, covering soil formation, properties and processes in greater depth. They visit unique soils like the 'buried podzol of Teinland' (FitzPatrick, 1965) and a relic tropical soil containing Macaulayite (Wilson et al., 2018) that may be found on Mars. As the weather deteriorates, laboratory practicals show theory in action and teach analytical approaches.

While field and laboratory practicals are common at many institutions, threats come from cost efficiency drives, workloads and the availability of lecturers with the necessary expertise. Aberdeen has decades of soil science teaching, but increasingly soil science is one of many subjects in environmental science or geography degrees. We need to adapt to ensure that the next generation of soil scientists are attracted to the discipline and trained at sufficient depth. Teaching of soil science used to be more collegiate between institutions, with sharing of resources and academics rewarded for writing textbooks. In the late 1990s, several UK institutions came together to produce "Soil Surveyor – Computer-assisted Learning for Land Literacy" (Dawson et al., 1997). Newer approaches facilitate virtual teaching, such as an online textbook with accompanying videos by Selker and Or on "Soil Hydrology and Biophysics". The British Society of Soil Science addressed field based and surveying teaching gaps by offering 'Working with Soils' courses that benefit from demonstrators with extensive expertise.

Great potential exists to improve soil science teaching for broader impact and greater student engagement. To address gaps in resources and expertise, collaborative teaching between institutions facilitated by national soil science societies is one solution. Soil scientists have been slow to embrace digital teaching, hindered by publisher resistance to digital modernization, but the value would be immense. How should we proceed? We will present options for discussion.

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# Publishing as an Early-Career Researcher in Soil and Water Conservation: Insights from International Soil and Water Conservation Research

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**ABSTRACT**

Early-career researchers (ECRs) face significant challenges in navigating the scholarly publication process, particularly in specialized fields such as soil and water conservation. This presentation draws on the editorial experience of International Soil and Water Conservation Research (ISWCR) to provide practical guidance for ECRs aiming to publish high-quality research. We first outline key steps for successful manuscript preparation, including aligning research questions with journal scope, structuring papers for clarity, and addressing reviewer feedback effectively. Emphasis is placed on the importance of rigorous methodology, transparent data reporting, and ethical compliance. Second, we highlight current hot topics in soil and water conservation that offer promising publication opportunities: (1) soil erosion modeling under climate change scenarios, (2) nature-based solutions for land degradation neutrality, (3) soil health indicators and their links to ecosystem services, (4) conservation agriculture in fragile ecosystems, and (5) integrated watershed management in the context of the UN Sustainable Development Goals. Finally, we discuss ISWCR's editorial policies that support ECRs, including constructive peer review, fast-track decisions, and open-access options. By bridging the gap between emerging researchers and the demands of high-impact journals, this presentation aims to empower the next generation of soil scientists to contribute meaningfully to global conservation efforts.

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# Indigenous Agricultural Terraces in Mexico

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**ABSTRACT**

Agricultural terraces modify natural soil conditions to make them suitable for farming. Mexico is considered a center of origin for this technology. Sites with ancient and modern terraces are distributed throughout the country, particularly in arid and semi-arid regions. Furthermore, anthropological studies have highlighted the importance of this agricultural technology as a key component of the hydraulic works that enabled the development of a pre-Columbian civilization in Mexico. Despite their prevalence and historical significance, the soils of agricultural terraces and the local soil classifications, still used by some indigenous peoples in Mexico, have been understudied. This work aimed to describe and classify the soils of stone-wall bench terraces, document the indigenous soil classification of the Popoloca people, and characterize the agricultural terraces in a community in the southern part of the State of Puebla, Mexico. Soil description and classification were conducted according to World References Base (WRB) criteria in three runoff terrace systems approximately 100 years old. The indigenous soil classification was determined through an ethnopedological study that incorporated local knowledge via interviews, transect walks, and participatory mapping. The characterization of the terraces was achieved through farmer interviews, field surveys, and photointerpretation. Nine soil profiles within the agricultural terraces were classified as Terric Anthrosols. In addition, Eutric Leptosols, Eutric Regosols, and Pellic Vertisols were identified in natural soils using official pedological charts. The indigenous soil classification system, in turn, defines eight soil classes based on their agricultural suitability. Anthropogenic soils are distributed across 2578 hectares of slope and runoff terraces, featuring specialized structures for support and drainage. The terrace walls exhibit various construction styles and materials; however, inhabitants recognize a traditional stone-wall type known as *cuaxustle*, which is associated with the oldest terraces described by the community. According to the farmers, the formation of a surface horizon suitable for cultivating maize and beans can begin as soon as two years after a terrace is constructed. Furthermore, the communal labor organization of the Popoloca people helps reduce terrace labor costs through cooperation. It is concluded that agricultural terraces can generate quality agricultural soils in terraced areas, which help guarantee part of the community's food supply. The terraces have facilitated agricultural development in the study area, forming optimal soils within a relatively short period.

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# Salary survey of soil science faculty in the United States of America: A gender comparison

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**ABSTRACT**

It is well established that women are often paid less than men for the same jobs in the United States of America (USA), but no survey of soil science salaries has been published. This study used publicly assessable databases to investigate the salaries of soil science faculty at colleges and universities. Salary data were collected for 2019 and 2022. Comparisons were made based on gender, land grant status, region, academic rank, and soil science specialization. Overall, men made more than women, but the gap shrunk from 12.8% in 2019 to 7.0% in 2022. Faculty at land grant institutions made more than those at non-land grant institutions and all faculty made more as their academic rank increased. The Southwest and New England regions had the highest salaries in both years, with a 2022 average above $132,000, while the Northwest and Southeast regions had the lowest averages. Most regions, except the South, had an increase in average salary from 2019 to 2022. The Northwest was the only region where women out-earned men, with a 7% difference in 2019 and 9% in 2022. The Great Lakes region showed huge improvement in gender equity with a gap that had nearly closed by 2022. New England, the Southwest, and the South had the largest salary gaps between women and men. Women trailed men for salary earnings at all academic ranks in 2019, but had caught or passed men at the instructor, assistant professor, and associate professor levels by 2022 and had narrowed the gap at the professor level. Soil physics faculty had the highest average salary in 2019 (soil chemistry was second), while soil chemistry faculty had the highest average salary in 2022 (soil physics was second). Soil physics and soil chemistry faculty positions in the USA are both dominated by men. Soil biology faculty had the lowest average salaries in both years of data collection. Soil biology is the only soil science subfield in the USA where there are as many women on faculty as men. Overall, the results of our study showed that women faculty members are still paid less than men, but the pay gap is decreasing and that gap has disappeared at the lower levels of soil science academia in the USA. This offers promise for a more equitable future for soil science faculty pay by gender in the USA.

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# Crop identity modulates the homogenization of soil microbial functions induced by long-term fertilization

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**ABSTRACT**

Fertilization practices are crucial for crop yield but profoundly affect soil microbial composition and functions. However, how they reshape microbial ecological functions, and whether these vary with crop types, remains unclear. Utilizing an 18-year field experiment with continuous maize, soybean, and wheat cropping, this study integrated amplicon and metagenomic sequencing to analyze microbial responses to NPK fertilization. The results revealed that fertilization consistently narrowed microbial niche breadth. Bacterial niche breadth decreased significantly in wheat (0.428 to 0.225) and soybean (0.488 to 0.324), with a marginal change in maize (0.427 to 0.417). Fungal niche breadth reductions were most pronounced in wheat (0.301 to 0.083), followed by maize (0.425 to 0.296) and soybean (0.443 to 0.388). Crucially, the changes in microbial niche breadth were closely related to shifts in life history strategies. Fertilization simplified microbial metabolic functions, driving a shift in life history strategies characterized by weakened capacity for complex substrate metabolism across all three crops. Furthermore, the microbial functions in continuous soybean and maize cropping soils were biased toward environmental response, whereas those in continuous wheat cropping shifted toward nutrient cycling. PLS-SEM confirmed that fertilization and continuous cropping regulate microbial life history strategies by altering soil nutrient levels, which subsequently constrain microbial niche breadth. Overall, this study demonstrated that long-term mineral fertilization tended to homogenize soil microbial function. Crop type acted as a modulating factor of fertilization effects, with microorganisms in wheat systems showing higher sensitivity. These findings provide new insights into the mechanisms by which long-term fertilization and continuous cropping affect soil microbial ecological functions.

**Keywords:** Long-term continuous cropping; Life history strategy; Mineral fertilization; Soil microorganisms

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# Two-Eyed Soil Seeing: Bridging Indigenous Knowledge and Science for Soil Security

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**ABSTRACT**

Achieving global soil security requires not only scientific innovation but also the respectful integration of Indigenous Knowledge Systems (IKS)—deep, place-based understandings of soil cultivated through generations of observation, interaction, and stewardship. These holistic perspectives align closely with the five dimensions of soil security—capacity, condition, capital, codification, and connectivity—yet remain underrepresented in contemporary research, policy, and practice.

This presentation suggests a possible transdisciplinary framework recognising ethnopedology, the study of Indigenous and local soil knowledge, as a bridge between cultural insight and scientific analysis. Ethnopedology provides a powerful lens for understanding how Indigenous communities classify, manage, and value soils through environmental indicators, oral traditions, and spiritual relationships with the land. By integrating these approaches with modern soil science and the soil security framework, we can reveal complex soil processes and sustainable practices often overlooked in conventional frameworks.

Central to this integration is the principle of Two-Eyed Seeing (Etuaptmumk)—learning to view the world from one eye with the strengths of Indigenous knowledges and from the other with the strengths of Western science, and using both together for mutual benefit. Combined with knowledge co-production, this model promotes genuine partnership rather than assimilation, where Indigenous knowledge holders and scientists collaboratively design research questions, methods, and outcomes.

Practical applications include establishing data sovereignty protocols, supporting intergenerational knowledge transmission, and creating enduring platforms for dialogue and co-learning. Recent efforts to quantify the “connectivity” dimension of soil security through indicators of knowledge, action, and attitude offer a means to measure the impact of these collaborations.

By weaving ethnopedological insights with scientific inquiry through Two-Eyed Seeing, this framework strengthens connectivity, fosters equity, and cultivates shared responsibility for soil stewardship—reimagining soil not only as a biophysical resource but as a living bridge between cultures, knowledges, and generations.

**Acknowledgments**

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# Digging Deeper: How Soil Re-engineering and Nitrogen Strategies Improve Root Growth and Yield in Barley and Triticale

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## ABSTRACT

Subsoil constraints such as acidity, compaction, and poor water-holding capacity remain major challenges to crop productivity across many Western Australian soils, particularly in duplex (Kurosol) and deep sandy profiles. These limitations restrict root exploration, nutrient uptake, and water use efficiency, ultimately reducing yield potentials. To address these issues, two semi-controlled soil column experiments were conducted to examine how deep soil re-engineering—through loosening, liming, and clay incorporation—interacts with nitrogen (N) fertiliser to influence crop growth, root development, and soil properties. In an acidic Kurosol, deep liming markedly increased barley (*Hordeum vulgare* L.) root length, surface area, and volumetric root length density, allowing roots to access deeper soil layers and rely less on surface moisture. Biomass and grain yield rose sharply under limed treatments, with yield continuing to respond linearly to added N. In contrast, unlimed soils showed yield plateaus at higher N rates. A complementary study on a sandy soil showed that triticale (× *Triticosecale* Wittmack) responded strongly to soil re-engineering, particularly where lime and clay were combined. These treatments promoted deeper rooting, greater biomass, higher grain yield, and improved N recovery. Regression tree analyses pointed to N rate, soil pH, aluminium, and clay content as major factors controlling yield and root traits. Across both studies, integrated physical and chemical amelioration improved subsoil pH, reduced exchangeable aluminium, and enhanced overall water and nutrient capture. Together, the results indicate that deep-profile amelioration, through lime and clay incorporation combined with well-managed N supply can sustain root growth and improve fertiliser efficiency in constrained soils.

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# Soil Memory in Karstic Terraced Landscapes: A Geoarchaeology Study of Montefalco Castle, Central Italy

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**ABSTRACT**

Mediterranean terraced landscapes document long-term human agency in mountainous environments, yet their soil histories remain poorly understood. The Castle of Montefalco (11th to 14th century A.D.) in central Italy is situated within a karst environment, surrounded by a system of walled terraces that date back to the Modern period, and possibly earlier. The construction of terraces reflects human efforts in creating flat land in mountainous regions for farming or agroforestry. An interdisciplinary geoarchaeological approach has been developed to capture the soil memory of terraces, integrating multiple scales of analysis from microscopic to landscape level. Soil micromorphology, image analysis of scanned thin sections, phytolith studies, µXRF geochemistry, and OSL profiling were combined to reconstruct formation processes and maintenance dynamics. Micromorphological evidence indicates biologically active soils with continuous bioturbation, while OSL depth profiles display a normal net signal progression, suggesting gradual sedimentation behind the terrace walls rather than abrupt anthropogenic dumping. The reconstruction of terrace fillings suggests the addition of reworked soils and rock fragments derived from nearby cherts and limestones. These findings contribute to understanding how soil processes, human management, and karst geomorphology interact to sustain agricultural practices over centuries.

# Oral Traditions from the Gangetic heartland of India

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**ABSTRACT**

The scientific study of soil has historically revolved around the themes of soil genesis, taxonomy, and fertility enhancement, primarily to optimize agricultural productivity. However, diachronic studies in the social sciences show that soil figures prominently in human life worlds, both as a medium for cultivation, and as a source and symbol of a shared cultural identity. Epistemologies surrounding soil partake of religio-cultural interpretations that venerate soil as the foremost provider of food and nutrition and as a symbol of fertility. Vernacular literature and poetic traditions often give rise to indigenous soil concepts in which scientific acumen, ecological sensibilities and sustainable livelihood are indivisibly interwoven.

In Hindi, 'mitti'— derived from the Sanskrit word 'mrittika'—epitomizes both the existential and symbolic relationship between people and terrain. India's expansive geographical diversity and climatic heterogeneity have led to a rich array of vernacular soil nomenclatures - 'bhangar' denotes the old alluvial deposits, 'khadar' signifies fresh alluvial formations; 'regur,' is widely recognized as Black Cotton soil; and arid expanses are distinguished by stratified layers of 'kanker'. Soil diversity has necessitated a useful taxonomy that has incorporated traditional knowledge, transmitted it orally through proverbs and idioms and codified it in agricultural records of the state.

Ghagh, the illustrious seventeenth-century North Indian poet-philosopher, exemplifies this synthesis - his agrarian aphorisms, celebrated across the Hindi-speaking heartland, encapsulate empirical insights into soil dynamics, climatic exigencies, and the agronomic wisdom guiding pre-modern farming. Weather forecasts, predictions of rain, use of organic fertilisers in farming, behaviour of birds/cattle/insects prior to rain, interpreting the signs of the seasons, folk perceptions of astronomy and other facets of environmental knowledge systems are interwoven inseparably with everyday peasant life in the world of Gagh-Bhaddar proverbs or Dak vachan. He nudged for organic farming through "Wohi kisanon mein hai pura, Jo chodey haddi ka chura" ie the one who uses bone and flesh meal in his fields can be regarded as a genuine farmer. Similarly, on crop distancing he wrote "Gajar, ganji muri, Teeneu boway doori" ie radish, sweet potato and carrot should be sown at a distance. These oral traditions, far from being merely folkloric, encode pragmatic prescriptions and timing for agricultural practices.

My presentation will focus on illustrating this interplay between primordial and modern soil knowledge to initiate a dialogue that transcends disciplinary silos and revitalizes our approach towards soil stewardship in a rapidly changing ecological milieu.

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# Traditional Ecological Wisdom: Bengali Proverbs and Their Insights into Soil Management

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**ABSTRACT**

Bengali proverbs, accumulated over centuries of agrarian experience in the fertile deltaic plains of Bengal, covering both the states of West Bengal in India and Bangladesh, offer profound insights into soil science, water management, and sustainable agriculture. This folk wisdom, passed down through generations of farmers, reflects an intricate understanding of soil-water relationships that remains relevant to contemporary soil conservation discourse.

The proverb *'Mati ar jol mile shona pholai'*, that is *'Soil and water together yield gold'* encapsulates the fundamental principle of soil-water synergy in agricultural productivity. This traditional knowledge recognizes what modern pedology confirms: optimal soil moisture is essential for nutrient availability and crop success. Similarly, *'Je matite phoshol hoy, shei matike shomman dao'* which translates as *'Honor the soil that yields crops'* emphasizes soil stewardship, anticipating contemporary concepts of soil health management. Bengali wisdom also addresses soil fertility management. The saying *'Gobar shona, matir pran*' which means *'Cow dung is gold, the life of soil'*, highlights organic matter's critical role in maintaining soil vitality, predating scientific understanding of soil organic carbon and microbial communities. The proverb *'Tin bochhore tin phoshol, mati hoy pathor'* or that *'three crops in three years turns soil to stone'*, warns against soil exhaustion through continuous cropping without adequate regeneration—a concept now termed soil mining.

These proverbs collectively, and several others that I will talk about, demonstrate that Bengali agricultural communities possessed empirical knowledge of soil texture, structure, fertility cycles, erosion, and hydrological processes long before formal soil science emerged. Their wisdom emphasizes soil as a living system that requires respect and balanced management rather than mere extraction. In the context of the Soil Water Congress 2026, examining these traditional ecological knowledge systems offers valuable perspectives for sustainable soil management. As climate change intensifies pressure on soil and water resources, integrating time-tested indigenous wisdom with modern scientific approaches may provide holistic solutions for soil conservation, water retention, and agricultural sustainability in the Bengal delta and similar agroecological zones worldwide.

**Keywords:** Oral tradition, West Bengal, Bangladesh, Bengali proverbs, traditional ecological knowledge, soil-water relationships

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# Gendered Dimensions of Soil and Agricultural Practices in Rajasthan's Arid Landscapes

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## ABSTRACT

Rajasthan's arid and semi-arid ecosystems, characterized by largely arid, fragile soils and recurrent droughts, pose significant challenges for sustainable agriculture. Within these landscapes, gender emerges as a critical yet under-explored determinant of soil management and agricultural resilience. This paper examines the intersection of gender, soil and sustainability through the lived experiences of women farmers in Rajasthan. Drawing on field-based insights and secondary evidence, it analyses how gendered divisions of labour and unequal access to education and technical knowhow, markets, land, quality agricultural inputs, extension services and awareness of government schemes shape soil health outcomes. Women, who constitute a major share of the agricultural workforce, are the custodians of indigenous soil-fertility practices and conservation knowledge - yet remain marginalised in formal decision-making and technological innovation.

Using a gender-transformative and intersectional lens, the paper situates soil conservation and enhancement and integrated soil health management within broader debates on climate adaptation, equity and sustainability. It argues that gender-responsive soil management through inclusive extension models, recognition of women's knowledge systems and equitable access to resources is essential for the restoration of degraded lands and enhancing productivity in both arid and non-arid regions. The findings call for integrating gender analysis into soil-science research, agricultural policy and climate-adaptation strategies to achieve the sustainable development goals (SDGs) on land, food-security and gender equality.

**Keywords:** Rajasthan, gender; soil management; women farmers; arid ecosystems; sustainable agriculture

# Profile of professor diversities (male and women) in Brazilian soil science

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**ABSTRACT**

Innovative projects are the major challenges in Universities around the world, requiring strategies to increase the level of diversity and innovation in universities. The study hypothesized that the diversity of professors is an alternative to increase innovation in Brazilian soil science. Results showed that the team of postgraduate students is composed predominantly of Brazilians (mean: 97%) with low participation of foreigners. Programs of attractiveness are commonly used by traditional Universities in Europe, North America, and China to recruit students around the world. In Brazil, 3% of international students are represented mainly by students from Latin America. The team of professors/researchers is composed predominantly of Brazilians (mean: 99%) with low participation of foreigners. However, the greater part of professors/researchers obtained their doctoral (partial/total) in American or European Universities. The interdisciplinary and collaborative conditions are to increase the innovation in projects (Nyström et al. 2018). The different groups of partners increase productivity with a mutual benefit in the project (Cowie and Mcnae, 2017). The masculine predominance in the team of postgraduate students was common in the last decade, with 50% more men than women. However, in 2017, there was an equivalence of 54% and 46% of males and females, respectively, due to an increase of 40 % of the female presence in Brazilian Soil Science. This is a great indicator of diversity in the team of postgraduate students that brings a different perspective to research. Our study demonstrated that this gap is not more present among the postgraduate students. OECD (2011) demonstrated that in OECD countries, women graduates are the majority in the fields of education, health and welfare, and humanities and arts. While men dominate engineering, manufacturing, and construction. There was a masculine predominance in the team of professors/researchers, with a difference of 82% compared to female presence, where for every six professors/researchers male, there is one professor/researcher female. If we link the data from the student team, we can observe that there is an increase in women as postgraduate students, but this increase did not reflect on the presence in Academies. Probably, in the next years, we can see the number of women as professors/researchers as a consequence of the higher number of women with postgraduate degrees in soil science. According to Ceci and Williams (2010), the low women's presence is also due to them-decided child and family care, leaving the academy. We understand that the performance of the professor/researcher is not associated with gender but with the opportunity of work in a great group/university and the self-efficacy to develop research and publish papers. Based on the results, we conclude that the diversity of the team of students is high; there is a need to increase the diversity in the profile of professors/researchers who can contribute to increasing the number of patents in Brazilian soil science. However, even in a diverse team, the performance of students and professors/researchers is strongly related to the level of individuals: this holds for all fields, positions, gender, and age groups.

**Acknowledgments**

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# Digital resources and automated questionnaires for soil science education across secondary and higher education in Mexico

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**ABSTRACT**

The teaching of Soil Science in Mexico is limited to a few university programs and to exceptionally rare secondary school systems. Moreover, the syllabi of soil-related courses and the current teaching resources in Mexico rarely keep pace with advances in soil science, and largely omit gender and diversity perspectives. Regions such as Latin America still have a male-dominated field, where most soil science teachers are male scholars (e.g., *Mexico*, Hernández *et al*., 2023; and *Brazil*, Wardzinski-Barbosa & de Araújo-Pedron, 2024). These gaps may exacerbate difficulties in transferring practical soil knowledge across diverse social contexts and reduce students' motivation to pursue careers in soil science. Here, we developed a series of audiovisual resources to enable students to engage with soils across diverse Mexican landscapes through multiple techniques and epistemologies of soil knowledge, fostering inclusion of diverse social, cultural, and gender perspectives in soil science education. Automated questionnaires were designed to assess the before-and-after process of students' knowledge acquisition, identify the main sources of learning, and evaluate their level of confidence in applying soil science concepts. The pedagogical design is based on situated and constructivist learning, emphasizing that soil knowledge may be improved through contextual practice, reflection, and collaboration at secondary and higher education systems. This project contributes to the National Autonomous University of Mexico's Educational Program (PAPIME PE102725, UNAM) and to the digital platform *Proyecto Suelox* (Institute of Geology – UNAM) by creating open-access educational materials while promoting inclusivity and contextualized soil science.

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# Soil Justice: A Radical Black Marxist Framework for Addressing Soil Contamination

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**ABSTRACT**

Soil contamination testing and monitoring is conducted in numerous locations for diverse reasons, including mandated cleanup and remediation of contaminated sites, built environment reconfiguration or expansion, and as part of negotiations for the transfer of properties. While soil testing and monitoring often become part of the political economy of legal or transactional structures to protect property owners from liability, and sometimes for larger public health studies designed to inform public agencies, what is less clear is how soil contamination monitoring benefits communities affected by soil contamination in places where they live, work, and play. Most soil contamination monitoring is conducted with due diligence and safety in mind, but the methods used rarely benefit communities or protect them from further exposure to contamination. Studies that engage with environmental justice in contaminated spaces help to illuminate why this conundrum exists. These include a lack of transparency from municipal governments when contaminant testing is conducted, poor regulation of contamination in general, and inadequate policy to prevent human exposure to contaminants. Yet, if soil contaminant monitoring were to contribute to improving social conditions, it would engage with transdisciplinary research that includes a broader array of methodologies and inquiries aligned with clear political commitments. The Black Radical Tradition and Marxism offer, in combination, such a possibility. A Radical Black Marxist framework is described and discussed relative to soil contamination to demonstrate how it enables greater engagement with the politics and values of those who are conducting soil contaminant monitoring and how it would be of more use to those impacted by contamination. Issues of upward translation and data sovereignty are discussed to illustrate the usefulness of Black Radical Marxism in addressing soil contamination more effectively than has so far been the case.

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# Operationalizing the Soil Information System Framework: a methodological approach to strengthening collaboration and strategic development applied through country roadmap workshops

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**ABSTRACT**

Developing a sustainable national Soil Information Systems (SIS) remains a critical challenge. Many countries lack systematic guidance on establishing and maintaining SIS that are technically robust and viable over the long term. To address this gap, the SIS Framework was developed as a structured methodological approach to assess, plan, and strengthen the enabling environment required for sustainable SIS development. The SIS framework extends beyond data availability and technical specifications - it incorporates financial, technological, institutional and capacity aspects that influence SIS resilience.

The SIS Framework is organized into four phases—initiation, planning and design, implementation, and operational—each comprising practical components with suggested activities, guiding questions, and recommended tools. Refined through iterative application and stakeholder feedback, the SIS framework provides an open-access, replicable methodology for identifying constraints, prioritizing interventions, aligning SIS design with national objectives, and promoting cross-sector partnerships.

The methodology has been applied through country-level roadmap workshops led by national agricultural institutes. These participatory workshops involve bringing together key SIS stakeholders—such as farmers, researchers, policymakers, or funders —in reviewing framework components such as envisioning, enabling environment, stakeholder needs, idealised system design, partnerships, data strategy, organizational plans and financial sustainability, culminating in a national SIS roadmap. This roadmap contains agreed next steps for collaboration between the key stakeholders for the development of the SIS. Structured feedback from each workshop improves its application in additional countries. Workshops have been conducted in Zambia -April 2024, Ghana -October 2024, Kenya -February 2025, Togo -June 2025, Liberia -August 2025, Sierra Leone -October 2025, and Nigeria -October 2025, with further deployments planned.

This presentation details the SIS Framework methodology, outlines the roadmap workshop process, and synthesizes lessons learned from national partners involved in its implementation.

**Acknowledgments**

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# Soil Art in Action: Transdisciplinary Pedagogy and Community Practice in the Healing Garden Project

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**ABSTRACT**

How can a color heal our relationship with the Earth? The Healing Garden project at Sichuan Fine Arts Institute presents the "New Van Dyke Brown"—a transformative metaphor for a transdisciplinary language of soil. Historically, Van Dyke Brown was a pigment mined from peat soil. We invert this logic of extraction into a ritual of return: the rich humus we create from campus kitchen waste (over 28 tons converted) becomes our palette. Using this "life-brown" in local food producing and painting/healing performance, we transform art-making into an act of ecological reciprocity.

This artistic ritual anchors a cyclical pedagogy that bridges art, science, and community:

Creating the Pigment: Through community composting, Bokashi, and vermicomposting, we produce fertile humus—our "New Van Dyke Brown."

Painting the Landscape: This living pigment nourishes Hugelkultur mounds and food forests, where soil fertility becomes visible as biodiversity and abundance.

Completing the Cycle: In the Therapeutic Kitchen, the harvest is foraged, cooked, and shared, physically incorporating the soil's vitality into our community.

This closed loop—from waste to humus, to food, to body—bridges the "metabolic rift" through tangible repair, and grounds the ethic of "soil care" in actionable cycles. By the 23WCSS, we will present our co-created "Soil Lexicon," demonstrating how a shared language of soil emerges not from terminology, but from embodied, artistic, and community-engaged cycles of care. We offer a pedagogical model for a transdisciplinarity that is felt, lived, and grown.

**Keywords:** Language of Soil, Transdisciplinarity, Eco-Art, Metabolic Rift, Permaculture

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# Soil Memory and Heritage: Foundations for Soil Literacy and the Codification of Soil Rights

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**ABSTRACT**

Soil literacy, the capacity to understand, interpret, and apply soil knowledge, requires more than scientific information: it depends on cultural, historical, and emotional connections that make soils visible and valued within society. This study examines how two complementary perspectives, soil memory and soil heritage, can strengthen soil literacy and support the codification of soil rights.

Soil memory refers to the long-term imprint of natural processes and human activities preserved in soil features, horizons, minerals, and organic markers. As an archive of environmental and cultural history, soil memory enhances scientific literacy by training observers to read soils as records of climate shifts, land-use changes, and ecological transformations. Its persistent traits constitute a form of natural capital, comparable to biodiversity, that merits protection, as soil self-organization produces unique and sometimes rare environmental legacies.

Soil heritage provides a parallel, culturally oriented perspective. It highlights soils of symbolic, ecological, or historical significance and situates them within landscapes, traditions, and identities. While soil memory deepens scientific understanding, soil heritage connects with society through emotional, cultural, and place-based values. It incorporates diverse ways of knowing soil, traditional, indigenous, sensory, and experiential, that complement scientific knowledge and help make soils relevant to citizens, educators, and decision-makers. In addition, by linking soils to quality foods (terroirs), land-based customs, and iconic landscapes, soil heritage serves as a powerful gateway to soil awareness.

Together, soil memory and soil heritage form two reinforcing pillars that broaden soil literacy beyond technical expertise. They also help to create conditions for recognizing soils as finite and irreplaceable entities whose protection may require both cultural norms and legal frameworks. Examples of legal personhood granted to natural entities illustrate how enhanced soil literacy can support the codification of nature's status within societal hierarchies, while also underscoring the central role of soil knowledge in informing conservation policy, from the design of regulatory frameworks and management plans to the long-term governance and effectiveness of nature reserves.

Ultimately, acknowledging soil memory and soil heritage as integral components of soil literacy can broaden public engagement, foster more sustainable soil management, and support emerging debates on the ethical and societal foundations of soil protection. In this context, the codification of soil rights offers a pathway to make the intrinsic and interconnected value of soils legible and actionable within policy, jurisprudence, and shared civic responsibility.

# Raising Soil Awareness through "Soil of the Year" Campaigns in Central Europe

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**ABSTRACT**

Public "Soil of the Year" initiatives have emerged in Central Europe as important tools for promoting soil literacy and strengthening public appreciation of soil diversity. Although the long-running German and Austrian campaigns began earlier, the region-wide landscape became more dynamic during the last decade: the Estonian "Soil of the Year" was launched in 2014, the Polish initiative in 2018, and the Slovenian and Hungarian programs in 2022. These national activities preceded and inspired the establishment of the global IUSS World Soil of the Year initiative, illustrating how regional experience contributed to the international recognition of soils as part of global natural heritage.

The selection of the Gleysol as the World Soil of the Year 2025—proposed by the Hungarian Soil Science Society—highlights this continuity and emphasizes the growing Central European contribution to soil awareness efforts. This paper provides a comparative overview of the Estonian, Hungarian, Polish, and Slovenian campaigns, focusing on their educational approaches, communication strategies, and societal relevance.

In addition, we aim to conduct an initial exploration of the online presence of these campaigns, including visibility patterns and forms of digital engagement. At this stage, the extent to which such activities translate into measurable increases in public awareness remains uncertain, yet mapping these trends may offer valuable insights into how soil-focused communication evolves across digital platforms.

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# Pathways to Inclusivity in Agricultural and Environmental Sciences

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**ABSTRACT**

In a world requiring **creativity, collaboration** and **innovation** to address the challenges of our changing planet, it is crucial for the Soil Science Society of America **(SSSA**), the American Society of Agronomy (**ASA**), and the Crop Science Society of America (**CSSA**) to develop robust programs and initiatives. The Societies (SSSA, ASA, CSSA) have recognized **Diversity, Equity**, and **Inclusion** (DEI) as a top strategic priority, with a focus on cultivating a welcoming and supportive culture within our professional societies. We acknowledge that enhancing diversity, equity, and inclusion fosters strength, creativity, and innovation in our scientific community.

The collective ASA, CSSA, SSSA Diversity, Equity, and Inclusion committee continues to expand its impact on the SSSA, ASA, and CSSA cultures, member experiences, and strategic priorities, while leading initiatives with a focus on inclusivity. The committee has made significant progress implementing recommendations from the 2022 DEI Recommendations Report. A Measuring Success report has recently been released to assess our progress. This report highlights the Societies' collective efforts and progress, aligning our metrics with the member experiences that shape them. Key features of the report include 1) a demographic summary (gender and ethnicity), 2) progress on the 2022 recommendations, 3) DEI-focused programming at the Annual Meeting (now CANVAS), 4) highlights from a recent DEI survey, and 5) future recommendations to continue advancement.

This presentation will highlight the Societies' collective work and provide an update on the progress achieved to date for this major initiative in fostering a more diverse, equitable, and inclusive community with SSSA, ASA, and CSSA.

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# Building the Future of Soil Science: Priorities in Workforce Development and Global Engagement

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**ABSTRACT**

The Soil Science Society of America (SSSA) is the leading scientific and professional organization in the United States (US) dedicated to the advancement and application of soil science as a foundation for life. SSSA aims to be a global leader advocating for soils through education and science and focusing on critical issues like food security, environmental quality, ecosystem sustainability, climate change, and human health. Along with its sister societies the American Society of Agronomy, and the Crop Society of America (ASA, CSSA), SSSA focuses on increasing engagement through workforce development, policy advocacy, certification programs and increasing the visibility of our sciences.

A significant and growing gap exists between the demand for and supply of expertise in our fields. Data from the U.S. Department of Agriculture show that graduates earning food/agriculture, natural resources, and environmental science degrees will only account for 61% of the demand for graduates with expertise in these areas. To address this challenge, the ASA is funding a two-year campaign dedicated to increasing awareness and interest in our sciences. The campaign aims to increase enrollment in agronomy, crop, and soil science programs at post-secondary institutions throughout the US. The goal is to develop a diverse workforce by educating students on career paths and highlighting the crucial role these professions play in ensuring food security, protecting the environment, and safeguarding human health.

The Societies (ASA, CSSA, SSSA) are committed to public outreach and policy advocacy. They actively reinforce their Science Policy activities to ensure the unique needs of soil science are represented to policymakers. This critical work includes engaging in advocacy for federal research programs related to agriculture and environmental sustainability, thereby supporting the foundational research necessary for global progress.

SSSA ensures the high standards of the profession through its certification programs. The Certified Professional Soil Scientist (CPSS) establishes and maintains high standards of knowledge, skills, and conduct for practitioners. Achieving the CPSS designation requires a bachelor's degree in soils, extensive coursework requirements, and successful completion of the Fundamentals of Soil Science exam. CPSS professionals are recognized as experts qualified to perform soil science work, such as land use evaluations and environmental consulting. Building on this success, SSSA is contributing to efforts within the IUSS Division 1 Working Group on International Accreditation with a goal of working with global partners to build an accreditation program for Soil Scientists. This program will be a trusted resource to the public for experienced certified soil scientists.

This presentation will highlight the accomplishments of SSSA in its major initiatives on workforce development, policy advocacy, and global certification efforts in soil science.

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# What would our soils say if they could speak?

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**ABSTRACT**

Pedology and Soil Education are soulmates: they complement each other and share common goals to promote knowledge, care, and love for soils. How can we care for something we don't understand? That is the key question.

Love for soil must be nurtured from early childhood. We can encourage children's first contact with soils of different textures and consistencies. How about moistening a sample of clay soil and turning it into play, as fun as modeling clay? In basic education, paints made from different soil colors should have a place alongside colored pencils. Looking at soil with imagination can be magical with pencil and paper, soil becomes poetry. As expressed by student Izabella Queiroz, who wrote that "soil is a love that must be returned"; a friend that nourishes and sustains us.The different Soil Orders, with their distinct features, can become fun characters. Who wouldn't be charmed by "Grandpa Lato," from the Fun Soil Profiles project, representing the LATOSSOLOS -Brazil's (SiBCS, 2025) most weathered soils? And so, we grow into adults - aware and responsible. We don't need to be pedologists or soil educators to value and care for our soils. This is a mission for everyone: to love, protect, and respect this living, essential resource, from which our food comes, and which plays multiple roles in nature. I invite you to see the soil with fresh eyes and to find, in the slopes by the roadside, precious life lessons. Walk barefoot on the earth, feel its energy. Never forget: the soil is alive. After all, what would our soils tell us if they could speak?

**Acknowledgments**

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# The Fun Soil Profiles according to the World References Base for Soil Resources

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**ABSTRACT**

In Brazil, soils are classified according to the Brazilian Soil Classification System (SiBCS, 2025) into 13 soil Orders, described based on their chemical, physical, mineralogical, and morphological attributes. However, the teaching materials used in basic education do not provide updated information on Brazil's soil Orders and often avoid the appropriate nomenclature due to its complexity. To address this and simplify the understanding of the 13 soil Orders in a creative and engaging way, the "Fun Soil Profiles" Extension Project was created in Brazil in 2019. The project features playful characters representing each soil Order: Latossolos (Grandpa Lato), Neossolos (Little Liti), Espodossolos (Mr. Spodos), Nitossolos (Star), Gleissolos (Gleyson), Chernossolos (Madame Chernossólica), Organossolos (Little Monster Organo), Plintossolos (Plintita), Cambissolos (Cambi), Vertissolos (Super Vertinho), Argissolos (Argi), Luvissolos (Luvi), and Planossolos (Plano). Subsequently, 12 characters were created based on Soil Taxonomy (2022) to represent the 12 major soil orders found in different landscapes: Alfisols (Alfi), Andisols (Vulcano), Aridisols (Aridilson), Entisols (Baby), Gelisols (Gelinho), Histosols (Cramby), Inceptisols (Young), Mollisols (Uncle Moli), Oxisols (Grandma Oxídica), Spodosols (Mr. Spodos), Ultisols (Ulti), and Vertisols (Maravilha).To further expand the project, the current work presents 32 characters created based on the key features of the 32 References Soil Groups defined by the World References Base for Soil Resources (WRB, 2022): Histosols, Anthrosols, Technosols, Cryosols, Leptosols, Solonetz, Vertisols, Solonchaks, Gleysols, Andosols, Podzols, Plinthosols, Planosols, Stagnosols, Nitisols, Ferralsols, Chernozems, Kastanozems, Phaeozems, Umbrisols, Durisols, Gypsisols, Calcisols, Retisols, Acrisols, Lixisols, Alisols, Luvisols, Cambisols, Fluvisols, Arenosols, and Regosols. Thus, the "Fun Soil Profiles" become important tools for soil education from basic to higher education, helping to illustrate the different types of soils in Brazil and around the world, highlighting their most important characteristics through characters in a playful, enjoyable, creative, and engaging way.

**Acknowledgments**

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# The Fun Soil Profiles: Characters for the YECS Working Group at WCSS 2026.

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**ABSTRACT**

With the aim of bringing young audiences closer to soil science in a playful, creative, and engaging way, two mascot characters were developed for the Young and Early Career Scientists Working Group at WCSS 2026. Dr. 土生 (Born from Soil) and the young student 地护士 (Nurse of Soils) represent the intergenerational spirit of this working group. Inspired by the World References Base for Soil Resources (WRB, 2022), these characters were designed with distinct shapes, colors, and personalities that reflect the main features of soils, making them easier to understand for children, youth, and adults. This proposal is part of the Brazilian initiative "Perfis de Solos Divertidos" (Fun Soil Profiles), which emerged from the national project Soil Education for All, active in Brazil since 2013. Dr. 土生 symbolizes the experienced soil science researcher and educator, while 地护士 represents a young student, connecting soil science concepts with different fields of knowledge and a critical view focused on soil health care. These mascots have been used in soil science events as educational tools, supporting outreach and the popularization of soil science from basic to higher education. This innovative approach strengthens the role of soil education in shaping young citizens who are aware of the importance of caring for and conserving the world's soils

**Acknowledgments**

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# Regional Assessment of Soil Compaction and Susceptibility in Salt-affected Arable Land in the Yellow River Delta

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**ABSTRACT**

The continuous increase in agricultural mechanization has led to intensified soil compaction degradation. It is crucial for ensuring the sustainable development of national agriculture by addressing soil compaction. Salt-affected soils, which are important reserves for arable lands, have experienced an increase in agricultural use in response to national demand in China, leading to an increased soil compaction risk. However, current research on soil compaction is mainly focused on non salt-affected soils, resulting in a lack of understanding of the compaction process and regional spatial and temporal variation. This study aims to assess the current status and potential risk of soil compaction at the regional scale in Dongying, eastern China. A regional survey was conducted based on 76 sampling sites across three soil layers (0–15, 15–30, and 30–45 cm). Soil compaction was evaluated using penetration resistance, shear strength, saturated hydraulic conductivity, soil water retention characteristics, and uniaxial soil compression curves. Key parameters derived from compression curves were used to characterize soil mechanical strength and susceptibility to compaction. Clear vertical differentiation of soil compaction was observed, with subsurface layers exhibiting higher penetration resistance, shear strength, and compressibility than the surface layer, indicating the widespread presence of mechanically restrictive layers. The soil salinization had a significant influence on soil compaction status and spatial differentiation of farmland soil. The results highlight the coupled effects of mechanical loading, hydraulic and salinization limitations on soil structural stability. By integrating compression behavior with mechanical and hydraulic indicators, this study provides a physically grounded framework for regional assessment of soil compaction status and risk. The results contribute to a mechanistic understanding of soil compaction processes and support the identification of areas vulnerable to soil structural degradation in coastal agricultural regions.

**Acknowledgments:**

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# Soil vocabularies: towards joint human and machine readable terminology

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**ABSTRACT**

Soil as a science and the application of the insights, knowledge and data generated by or related to that science is a broad domain with many different subdomains, topics, adjacent domains, applications, and stakeholders. All these domains have their own agreed or de facto terminology that they use to communicate with each other, e.g. on research topics, concepts and procedures used, and apply in metadata, databases, knowledge documents. These are often agreed and written down in documents, such as the WRB and national soil classifications and description standards, soil legislation (e.g. the EU Soil Monitoring Law), ISO and GLOSOLAN lab procedures, etc. They can also be defined in projects or literature. In general they are described as glossaries in documents or on websites, which makes them human understandable but not easy to find, re-use, govern, maintain or cite.

To make the terminology, the glossaries, definitions and vocabularies of soil science and other domains machine readable, citable, easy to find, use and govern by the soil community, online vocabulary repositories or registries exist, e.g. AGROVOC[ https://www.fao.org/agrovoc/ ] and GEMET[ https://www.eionet.europa.eu/gemet/en/about/ ]. These repositories store the terms, definitions, relations to other terms, translations of terms in different natural languages, a link to the References (document) for the term and a unique identifier. Each repository has a webpage where users can consult the repository, and a governance body. The latter consists of domain experts who can decide on governance issues such as requests for additions, changes of terms, definitions, linkages etc. and may apply a hierarchy based on authoritativeness of terms. A proposal is to give pReferences to definitions and terms in legal documents, then adopted standards, then subcommunity de facto standards, literature Referencesd and project vocabularies.

At present, in the soil domain the last step of digitization, storage and governance of soil related terms in an online vocabulary repository is often not done yet, severely limiting soil information FAIRness (Findable, Accessible, Interoperable, Reusable). However, a few recent developments are promising. In the framework of the EU's Mission Soil, all Mission Soil projects collaborate in a Cluster on Knowledge and Data Management assisted technically by the SoilWise project. Within IUSS the WRB WG (governance and content) and the SIS WG (technical assistance) collaborate. At ISRIC increased attention to vocabularies allows to address remaining roadblocks. At the Global Soil Partnership (GSP) a GloSIS WG was created with vocabularies as subtopic. This increased attention, international collaboration and activity on the topic can lead to mature and useful soil vocabularies in a few years, significantly increasing the possible FAIRness of soil information.

**Acknowledgments**

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https://www.fao.org/agrovoc/
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# The evolution of soil science research in Portugal since the 19th century

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**ABSTRACT**

This study analyzes the historical evolution of Soil Science in Portugal from the 19th century to the present. The central structural challenge identified throughout this period is summer water scarcity, a consequence of Portugal's Mediterranean climate (Köppen: Cs) and the limited water storage capacity of its soils. This issue is further exacerbated by low Soil Organic Matter (SOM) levels, shallow effective soil depth, and light textures.

Since the early research led by pioneers Ferreira Lapa (1823–1892) and Luís António Rebello da Silva (1855–1946), the chronic deficiency of SOM has been a primary driver of scientific inquiry. Influenced by breakthroughs in France, England, and later the USA, Portuguese research expanded into crop fertilization, soil conservation, and mapping. A major milestone was the 1950 Agrological Mission (Figure 1), which initiated the study of tropical soils under the leadership of Joaquim Botelho da Costa (1910–1965), the "Father of Soil Science in Portugal."



*Figure 2 Team of the Tropical Pedology Study Brigade from the Instituto Superior de Agronomia (Lisbon), comprising Rui Mayer, Botelho da Costa, Ário Azevedo, Rui Pinto Ricardo, and sixteen staff members; Angola, 1951.*

Despite the rise of soilless culture since the 1980s, soil remains the fundamental pillar for mitigating water scarcity. Current research focuses on enhancing soil fertility and crop yields as contingency measures against Global Change. Finally, the strong master-disciple continuity across generations has ensured efficient knowledge transfer, directly contributing to the evolution of plant production and human well-being in Portugal.

**Keywords:** evolution of knowledge, Mediterranean, rainfed, soil mapping, soil organic matter

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# Source to risk receptor transport and spatial hotspots of heavy metals pollution in peri-urban agricultural soils of the largest megacity in China

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**ABSTRACT**

The traditional concentration-based health risk assessment of heavy metal (HMs) pollution in soil has often overlooked the initial loading and toxicity differences of HMs from various sources. This oversight hinders effective identification of the risky source, complicating precise risk management of soil HMs pollution. This study applied a source-oriented health risk assessment framework that integrates source profiling, exposure risk assessment, and spatial cluster analysis. Taking the Shanghai City, the largest megacity in China as a case, the findings revealed that overall environmental quality of peri-urban agricultural soil in Shanghai remains good, though 3.03% of Cd concentrations exceeded the national References standards. Industrial & traffic activities, primarily contributing Hg, Cd, and Pb, accounted for the highest proportion (44.3%) of total metal concentrations and posed the greatest non-cancer risk (54.6% for children and 53.1% for adults). Notably, natural activities, mainly contributing Cr, ranked only third in concentration contribution (26.55%) but induced the highest cancer risk (58.55% for children and 57.08% for adults). These findings suggest that sources with lower concentration contributions may still pose significant health risk. Integrating source apportionment with health risk assessment can more precisely identify the risky source and target areas for mitigating the human health hazards.

**Acknowledgments**

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# Soil Dashboards creation and soil information systems: The case for Ghana

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## ABSTRACT

**Introduction**

Soil health is a continental priority to be addressed. African Union Member States have committed to coordinated action plan through the CAADP and Africa Fertilizer and Soil Health. The donor community has responded positively to addressing the challenges of soil information. Several initiatives addressing soil information systems have emerged in recent years. These include Soils for Africa Project, African Union Soil Observatory (AUSO), NORAD-CIFOR-ICRAF-VARDA Foundation-CA4SH, Development Gateway an IREX Venture, Food and Agriculture Organization Soilfer Project among others. Each of the initiatives is creating a dashboard or collaborating in the creation of dashboards. CSIR-Soil Research Institute in Ghana is pivotal in the implementation. Major challenges for successful creation of dashboards are data sharing, data quality and harmonization and co-creation of mutually beneficial collaborations. This article identifies challenges associated with dashboard creation for soil information systems and explore opportunities for creating co-benefits among international and local collaborators.

**Materials and methods**

The Projects goals, objectives, duration expected outputs and deliverables, alignment with global, regional and national agenda, donors, partners, capacity building opportunities, communication, infrastructural development and existence ofFAIR (**F**inadable, **A**ccesssible, **I**nteroperable, **R**eusable) data guidelines were reviewed.

**Discussion**

All the initiatives are delivering a dashboard of soil information in Ghana. AUSO dashboard is focusing on continental scale delivery, but national focus is a priority. All the initiatives involve active stakeholder engagement. This is generally good, but effort should be made to avoid stakeholder fatigue. A good stakeholder matrix aligning interest and initiatives goals is needed.

**Conclusion:**

FAIR data guidelines, capacity building/succession plan, regular training in data management are important for successful dashboard creation and mutually beneficial collaborations. All the initiatives involve CSIR-SRI. Infrastructure and capacity building efforts are needed for hosting the dashboards. Ghana could be prioritized for monitoring and evaluation of soil information in Africa.

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# Community-based research and action for sustainable land use in the Ethiopian Rift Valley

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## ABSTRACT

Two linked collaborative research projects in Ethiopia will be presented that address land degradation, soil restoration, biodiversity and rural livelihoods through strong partnerships between Ethiopian institutions and UK-based researchers. Both initiatives exemplify community-led research, meaningful local engagement and capacity building with demonstrable impact.

The project, “Local-level land degradation assessment towards sustainable land management for improved livelihood in the Ethiopian Rift Valley” (REDAA-SMILE) uses community-based participatory approaches to co-develop action plans that respond to locally expressed needs. Through joint land degradation assessment and low-cost site-specific interventions, the project is actively achieving degraded land restoration and fostering business models that strengthen livelihoods—especially for women, youth and unemployed groups. The design explicitly integrates indigenous knowledge, local stakeholder perspectives and gender-sensitive strategies, ensuring that farmers understand both problems and solutions in their own contexts and can independently sustain and scale activities. This approach has already fostered local ownership and practical solutions to entrenched environmental challenges such as soil erosion and food insecurity.

The project, “Cataloguing and Rating of Opportunities for Side-lined Species in Restoration of Agriculturally Degraded Soils in Sub-Saharan Africa” (GCBC-CROSSROADS) explores harnessing native floral diversity to restore agriculturally degraded soils in Ethiopia. Combining systematic reviews, field and laboratory studies, socio-economic analysis and local community engagement, the project seeks to understand how these plants influence soil health, biodiversity, climate resilience and livelihoods. A key strength of this work is the integration of local ecological knowledge and farmer perspectives into scientific characterisation and modelling, reinforcing the relevance and uptake of restoration practices. Collaborative activities—including improving laboratory facilities in Ethiopia, joint field visits and bi-directional sharing of teaching —illustrate substantive capacity building and co-production of knowledge.

Both projects demonstrate successful institutional cooperation that values local leadership and indigenous knowledge, supports Ethiopian research capacity and yields insights relevant for scalable soil restoration and rural prosperity. The UK-funded SMILE project is notably led by the Ethiopian partners, underscoring the emphasis on local ownership in driving sustainable impact across ecosystems and communities.

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# Viruses of nitrifying prokaryotes and their impact on soil nitrogen cycling

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**ABSTRACT**

Viruses influence biogeochemical cycling through cell lysis and metabolic reprogramming, yet the consequences of virus–host interactions in soil remain poorly resolved in these complex, diverse ecosystems. We demonstrate that focusing on discrete, microbially-mediated biogeochemical processes provides a powerful framework for illuminating soil virus–host dynamics. Nitrification is a central process in the nitrogen cycle, regulating nitrogen availability while contributing to nitrous oxide emissions and nitrate leaching associated with inefficient fertiliser use in agriculture. Viruses of ammonia- and nitrite-oxidising microorganisms that perform nitrification have received comparatively little attention. This is likely, in part, due to cultivated strains being incapable of confluent growth on agar plates, limiting the use of plaque assays for isolating lytic viruses. Using a novel liquid-based approach with a pre-incubation step to enrich both active hosts and viruses, we cultivated viruses infecting a range of ammonia-oxidising archaea (AOA) and bacteria (AOB) strains, with stable cultures analysed using transmission electron microscopy and genome sequencing. Viruses of both AOA and AOB were diverse and belonged to multiple uncharacterised families, all possessing minimal similarity to cultivated virus References genomes. In agreement with our previous virus-targeted metagenomic analyses, AOA virus genomes are generally larger than AOB, and ranged in length from 39 to 160 kb and 36 to 51 kb, respectively. AOB virus infection resulted in typical virus-host dynamics associated with the lytic life cycle, whereas AOA viruses produced host growth dynamics associated with chronic infection and caused host cell gigantism. The cultivation of nitrifier viruses offers opportunities for the development of novel genetic tools and augmentation of nitrification rates in various ecosystems.

# How do nitrogen transformation processes affect nitrogen use efficiency in rice paddy

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**ABSTRACT**

The nitrogen (N) use efficiency (NUE) of cropping systems needs to be improved to achieve sustainable agricultural development. The NUE of rice production in China is known to be lower than that in other major rice-growing countries; however, there are large regional variations in NUE across the country, and the underlying mechanisms driving this variation remain poorly understood. We collected soils from 50 rice paddy fields in the main rice production areas of China, quantified the rates of N transformation, characterized the associated microbial communities to explore the linkage among environmental controls, process rates, the responsible communities and NUE. We show that NUE in Chinese rice paddies is strongly associated with the ammonium retention time and gross rates of oxidation of NH4+ and N mineralization; additionally, we propose that soil pH and microbial composition are major factors determining soil N transformation processes and NUE. In particular, the variation in NUE in the sampled soils was strongly associated with changes in the relative abundance of Nitrososphaerales, an archaeal order encompassing diverse ammonia oxidizers. These findings provide important insight regarding the mechanisms underlying the large regional variations of rice NUE in China and offer a blueprint for improving the management practices in rice production systems.

# Global Soil Nitrogen Budget and Pollution hotspots (1980–2022)

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## ABSTRACT

Soils mediate the largest exchanges of reactive nitrogen (Nr) between the biosphere, atmosphere, and waters. Using the coupled human and natural system model CHANS-Globe, we construct a soil-centred global nitrogen budget for 1980–2022 that integrates mineralization, nitrification, denitrification, plant uptake, manure and fertilizer management, and soil–water solute transport. Harmonizing multi-source datasets and validating against soil, riverine, and atmospheric observations, we resolve trends in soil N stocks, soil-derived atmospheric emissions ($NH_3$, $NO_x$, $N_2O$), and nitrate leaching/runoff. Anthropogenic Nr inputs increased by 40-50% over four decades, accompanied by higher atmospheric emissions and intensified solute exports. Pollution hotspots are identified in East and South Asia, Western/Central Europe, the U.S. Corn Belt, parts of Latin America, and major African river basins, driven by high fertilizer intensity, concentrated livestock, drainage practices, and limited wastewater treatment. We estimate a global net soil N sink of 30–100 Tg N $yr^{-1}$, with pronounced regional redistribution and divergent soil states ranging from N saturation to N deficiency, implying tailored management needs. Portfolio interventions, e.g., 4R nutrient stewardship, inhibitors/slow-release fertilizers, cover crops, manure stabilization, and drainage control, can cut Nr losses while improving soil health and nitrogen use efficiency. This study quantifies key processes and imbalances in the global soil nitrogen cycle, guiding efforts to synergistically achieve food security and environmental protection.

**Acknowledgments**

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# Mineral-Microbial Interactions Drive Variation in Nitrogen Transformation Characteristics During Entisol (Purple Soil) Development

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## ABSTRACT

Entisols (commonly known as purple soils) in the Sichuan Basin of China are vital yet vulnerable agricultural resources, where significant nitrogen (N) loss poses a challenge. While surface N dynamics have been documented, a systematic understanding of N transformation patterns throughout the soil profile—and the role of mineral-microbial interactions in governing them—remains limited.

This research bridges this gap by investigating how the co-evolution of soil minerals and microbial communities regulates N transformation processes along profiles of Entisols derived from different parent materials (forming Calcareous, Neutral, and Acidic subtypes) under varying land-use types (Paddy, Dryland, Forest). We collected soil samples by genetic horizon from representative profiles in the hilly Sichuan Basin.

A multi-faceted analysis was performed on each horizon, encompassing: i) basic physicochemical properties, ii) mineralogical composition (characterized via XRD and FTIR), and iii) N transformation characteristics (quantifying gross mineralization, nitrification, and immobilization rates using $^{15}N$ isotopic tracing). To explicitly link mineralogy to microbial drivers, we analyzed the structure and functional potential of N-cycling microbial communities (targeting *amoA, nirS, nirK*, and *nosZ* genes) and related enzyme activities.

Our results demonstrate that profile-dependent evolution of distinct mineralogical assemblies (e.g., illite, smectite, kaolinite) and carbonate content acts as a primary environmental filter, shaping the ecological niches for N-cycling microorganisms. Specifically, the carbonate-buffered higher pH in calcareous subtypes selected for a bacterial-dominated nitrifying community (AOB), resulting in accelerated nitrification rates. Conversely, the mineralogy and inherent acidity of acidic subtypes favored archaeal ammonia oxidizers (*AOA*) and promoted greater N retention. This evidence shows that the soil mineral matrix directly and indirectly—through its control on pH and organic matter stabilization—orchestrates the microbial engine that drives N transformations.

By integrating mineralogical, microbiological, and process-rate data, this study establishes a mechanistic framework for the "Mineral-Microbial Interaction" pathway that controls N cycling during initial soil development. Our findings provide a scientific basis for designing precise N management strategies that account for subsurface biogeochemical heterogeneity in Entisols.

**Keywords:** Entisols, Nitrogen Transformation, Mineral-Microbial Interactions, N-cycling Microbes, Profile Variation, $^{15}N$ Isotope Tracing

**Acknowledgments**

This research was funded by the National Natural Science Foundation of China (NSFC) (Grant NO. U22A20562 and 42577363).

# Root-soil interactions govern soil organic nitrogen dynamics under acid rain and nitrogen deposition

**ABSTRACT**

Acid deposition and nitrogen (N) enrichment are major environmental stressors under anthropocene change, exerting severe negative impacts on N cycling in forest ecosystems. Fine roots, as the primary input source of soil organic nitrogen (SON), their decomposition process play a critical role in the formation and turnover of SON; However, how fine root decomposition mediates changes in root substrates and the soil microenvironment, thereby influencing SON dynamics under acid rain and N deposition, is still poorly understood. Here, we established an acid rain-nitrogen deposition simulation platform in subtropical Cunninghamia lanceolata plantations and conducted experiments using substrate regulation, environmental regulation, and in situ decomposition experiments to explore the interactive effects of fine root substrates and soil environments on SON dynamics. The results showed that fine root substrate treatments accelerated the decomposition of SON fractions, with SON fractions declining by 7–42% relative to the control. Soil microenvironmental changes had distinct effects: N addition increased accumulation of acid-hydrolyzable total nitrogen, amino sugar nitrogen, and acid-hydrolyzable ammonium nitrogen by an average of 15%, along with increased protease activity in higher-order roots. In contrast, acid rain treatment suppressed soil enzyme activities in lower-order roots, leading to a 20% increase in acid-hydrolyzable amino acid nitrogen content. Notably, root-derived substrates and soil environmental conditions acted synergistically to increase acid-hydrolyzable total nitrogen by 16–32% compared with the control. Redundancy analysis and random forest modeling identified soil pH, total N, and protease activities (acidic protease, chitinase, and aminopeptidase activities) as key predictors of SON transformation. Overall, our results suggest the need to consider interactive regulation of SON dynamics by fine root substrates and soil environmental conditions in climate change impact assessments of N cycling in terrestrial ecosystems.

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# SmartField Solutions: Advancing $N_2O$ Mitigation in Danish Agriculture

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**ABSTRACT**

Denmark's ambitious target of reducing national greenhouse gas emissions by 70% by 2030 underscores the urgent need to mitigate nitrous oxide ($N_2O$) emissions from agriculture. This is because fertilized soils contribute approximately 80% of the country's $N_2O$ sources. As part of SmartField, an innovative climate platform aimed at reducing Danish agricultural $N_2O$ emissions, we investigated mitigation strategies in a grass-clover/maize rotation on sandy loam at Supersite A (Aarhus University, Denmark). Using a randomized complete block design (4 blocks, eight treatments, 32 plots of 15 × 3 m), we compared the use of cattle slurry and biogas digestate, each combined with either (i) the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP; Vizura®), (ii) a 20% reduction in N rate plus DMPP or (iii) an additive for slurry (Eminex®), against a no-nitrogen (N) control. Manures were injected in two to three applications between April and July 2025. High-frequency automated chambers monitored $N_2O$ fluxes, complemented by measurements of mineral N dynamics and N leaching using suction cups. The study tested three a-priori hypotheses: (H1) DMPP would reduce $N_2O$ emissions for both substrates; (H2) moderate reductions in N application rate and optimized timing would lower cumulative $N_2O$ emissions without compromising the N fertilizer replacement value; and (H3) the slurry additive would suppress short-term $N_2O$ peaks without increasing N leaching. By integrating gaseous flux measurements, leaching data, and agronomic performance, the experiment aimed to identify mitigation strategies that would avoid pollution swapping while remaining effective across various manure types and management practices.

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# Substantial underestimations of soil nitrogen gaseous losses from global croplands under warmings

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**ABSTRACT**

Temperature sensitivity (Q10) of NO and $N_2O$ emissions are the core parameter to project future trajectories of soil nitrogen (N) dynamics in response to climate warming. However, spatial variations in Q10 and their underlying microbial pathways are unknown, hindering the ability of projection. We sampled 21 upland soils across a 4000-km transect in China and conducted incubations at 15 to 40 °C with $^{15}N$ tracer to quantify temperature response of process-specific NO and $N_2O$ emissions. We found that their optimal temperatures (Topt) exceeded 30°C and increased with mean annual site temperature. Q10 ranged widely from 1.3 to 5.7 (averaged 3.3) and 1.0 to 5.9 (averaged 3.5) for NO and $N_2O$, respectively, being higher in subtropical and warm temperate regions than others and being significantly higher than 2 as set in Earth system models. Using spatially variable Q10 values observed in this study would result in 10–40% larger NO and $N_2O$ emissions under Shared Socioeconomic Pathways (SSP) 1-2.6 to SSP5-8.5 scenarios by 2100, compared to those using a value of 2, suggesting previously substantial underestimation.

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# Comparative experiments and analysis of water and nitrogen dynamics in bare and rice fields using HYDRUS-1D

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## ABSTRACT

China is the world's largest consumer of nitrogen (N) fertilizer in rice production, yet excessive application leads to low nitrogen use efficiency (NUE) and significant environmental risks. This study investigated optimized water and N management through a two-year experiment with bare field in 2020 and rice field in 2021 and HYDRUS-1D modeling, analyzing conventional flooding (CF) versus alternate wetting and drying (AWD) with 30-40% N reduction and their effects on dry matter weight (DMW), NUE, $NH_4^+$-N and $NO_3^-$-N migration. Results showed AWD enhanced soil redox **fluctuations**, boosting nitrification and increasing $NO_3^-$-N uptake to 25-30%, which was 11-16% with CF. Root water retention under AWD reduced N concentration at 30 cm depth by 70% versus bare soil. CF with 30% N reduction maintained high yield of 1000 grain weight = 22.31 g and peak NUE= 45.63%. 1-3 days after each fertilization were critical for $NH_4^+$-N leaching particularly when irrigation exceeded 2 cm· $d^{-1}$. Notably, reflooding after drainage in AWD spiked $NO_3^-$-N by 40%, primarily from oxidized adsorbed $NH_4^+$-N. The HYDRUS-1D model demonstrated high accuracy for simulating water and nitrogen transport in bare and rice fields, particularly under CF conditions. And the model successfully revealed rice's predominant absorption of $NH_4^+$-N and the phenomenon that AWD irrigation increases the proportion of $NO_3^-$-N uptake. **For sustainable rice production,** CF system with 20-25% N reduction was suggested to balance yield, NUE and environmental protection, providing a **scientific** basis for optimizing water and N management in rice fields.

**Keywords:** HYDRUS-1D; alternate wetting and drying; nitrogen use efficiency; $NH_4^+$-N and $NO_3^-$-N concentrations

**Acknowledgments**

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# The disparity between canopy and understory N deposition in regulating soil $N_2O$ emissions in a Moso bamboo forest

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## ABSTRACT

Enhanced anthropogenic nitrogen (N) deposition has intensified nitrous oxide ($N_2O$) emissions from forest soils. The increase in atmospheric $N_2O$ concentration not only exacerbate the greenhouse effect but also aggravates stratospheric ozone depletion. However, most previous studies in forest ecosystems have relied solely on understory N addition for N deposition simulation, overlooking the influence of the forest canopy. Moreover, the majority of these studies have focused exclusively on inorganic N, with limited research addressing organic N deposition. Although the total N deposition seems to be stabilized in recent years, emerging evidence shows that atmospheric N deposition hotspots are shifting from temperate to subtropical and tropical regions. Here we conducted an experiment in a subtropical Moso bamboo (*Phyllostachys edulis*) forest to compare the effects of different N deposition simulation approaches (canopy vs. understory) and N forms (inorganic vs. organic). Our findings demonstrated that the annual cumulative soil $N_2O$ emissions under understory inorganic N deposition were 25.1% higher than that under understory organic N deposition. In contrast, no significant difference was observed between canopy organic and inorganic N deposition. For different simulation approaches, annual cumulative soil $N_2O$ emissions were always markedly higher under understory N deposition compared to canopy N deposition, but prolonged N deposition diminished the differences between the two approaches. In addition, both inorganic and organic N deposition increased abiotic $N_2O$ production by 17.2% and 16.5%, respectively, but abiotic processes only contributed 14.5-16.2% of total $N_2O$ emissions. Microbial processes dominated $N_2O$ production in both inorganic and organic N treatments, with nitrifier denitrification accounting for 54.6-64.3%. Furthermore, regardless of N forms, ammonia oxidizing bacteria (AOB)-driven $N_2O$ production (42.9-48.1%) exceeded that of ammonia-oxidizing archaea (AOA). The $N_2O$ emission factor from N deposition ($EF_4$) under canopy N deposition (0.76%) was lower compared to understory N deposition (1.63%). Using $EF_4$ derived only from understory deposition would lead to an overestimation of soil N2O emissions from Chinese bamboo forests by ~2.29 Gg $yr^{-1}$. Overall, our findings demonstrate that understory-only N addition experiments may substantially overestimate regional $N_2O$ emissions, particularly when inorganic N is applied, and underscore the necessity of incorporating canopy processes in future assessments of atmospheric N deposition impacts.

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# Dissolved Organic Nitrogen Losses in Organic Lettuce Systems: Challenging the Texture Paradigm

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## ABSTRACT

Long-term nitrogen (N) budgets from organic lettuce systems in California's Central Coast reveal substantial unaccounted losses (up to 350 kg N/ha annually) that cannot be explained by conventional inorganic N pathways. An emerging view is that in organic systems, where fertilizers such as manure and compost are rich in organic N, dissolved organic nitrogen (DON) can represent a significant portion of dissolved N leaching losses, as much as 35% of total N leached (Liang et al. 2021). However, the factors controlling DON leaching remain poorly understood; soil texture is widely considered a primary determinant of N mobility, while management practices and soil organic matter characteristics have been proposed as potential controls. Here, we combined controlled greenhouse experiments with field observations across 28 commercial organic lettuce farms in the California Central Coast region to test whether texture predicts DON leaching risk and identify effective soil management strategies. Column experiments (n=150) demonstrated that sandy soils leached 5.7-fold more DON than clay soils (13.6 vs 2.4 kg N/ha, $p<0.001$), with DON comprising 39% of soluble N in sand versus only 5% in clay. However, field observations across farms spanning 6-60% clay revealed no detectable texture effect on DON leaching risks ($p=0.71$). Instead, soil management practices explained 32-fold more variance than texture, with crop diversity and cover cropping emerging as the strongest predictors. Additionally, mineral-associated organic matter nitrogen (MAOM-N) was also found as another strong predictor of reduced DON leaching risks ($p=0.026$); further, increased cover cropping was found to be highly correlated with increased MAOM-N (0.005). These findings show that while soil texture fundamentally controls DON mobility under controlled conditions, field-scale complexity renders it an unreliable predictor of actual leaching risk. These findings challenge texture-based risk frameworks and demonstrate that management interventions—particularly crop diversification, cover cropping, and optimized nitrogen application—provide substantial leverage for reducing DON losses across all soil types.

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# Modeling soil HONO emissions

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**ABSTRACT**

Soil is a critical component in the Earth system, significantly influencing atmospheric chemistry and climate change. Soil nitrous acid (HONO) emissions represent a significant source of atmospheric HONO, directly impacting air quality and atmospheric chemical processes. However, due to the reactive nature of HONO, the influencing factors and mechanisms underlying its soil emissions remain controversial, which limits the estimation of regional soil emissions. This presentation focuses on the processes and mechanisms of soil HONO emissions, as well as data-driven, empirical, and process-based models for estimating soil HONO emissions, with the aim of providing scientific basis and support for reducing nitrogen loss and optimizing air quality.

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# The process of dissimilatory nitrate reduction to ammonium mediated by microorganisms

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**ABSTRACT**

Microbially mediated dissimilatory nitrate reduction to ammonium (DNRA) plays a crucial role in maintaining nitrogen balance in soil ecosystems. Previous studies suggested that DNRA occurs exclusively under anaerobic conditions, and mechanistic research on DNRA has likewise been confined to anaerobic environments. Our group previously demonstrated that *Pseudomonas putida* Y-9 can perform DNRA under aerobic conditions, with the *nirBD* genes involved in the reduction of nitrite ($NO_2^-$-N) to ammonium ($NH_4^+$-N); however, the key subunits responsible remained unidentified.

In this study, we constructed *nirB* and *nirD* gene knockout strains (Δ*nirB*, Δ*nirD*) and complementary strains (Δ*nirB::nirB*, Δ*nirD::nirD*) using double homologous recombination and seamless cloning techniques. By employing $^{15}N$ isotope tracing, we investigated the transformation of nitrate ($NO_3^-$) and $NO_2^-$ by these strains. The results revealed that the aerobic DNRA process in strain Y-9 is co-regulated by the *nirB* and *nirD* genes (Table 1). Further research identified that four out of eight preserved strains (isolated from long-term flooded paddy fields) could reduce $NO_2^-$ to $NH_4^+$ under aerobic conditions. $^{15}N$ isotope tracing confirmed the aerobic DNRA capability of these four strains. Sequencing analysis showed that the four strains showed the same NirBD sequence with strain Y-9 (the similarity was about 94.61%) (Fig.1). Additionally, two strains capable of reducing $NO_3^-$ to $NH_4^+$ under aerobic conditions—*P. fluorescens* 2P24 and *Agrobacterium tumefaciens* M—were isolated from upland farmland soil. Genomic sequencing confirmed the presence of *nirBD* genes in both strains, indicating their ability to perform aerobic DNRA.

Based on these collective findings, we hypothesize that the aerobic DNRA process is widespread in the surface layer of upland soils with sufficient oxygen. Consequently, the team conducted a meta-analysis of the soil DNRA process in subtropical regions. This analysis revealed that the DNRA rates in four typical subtropical ecosystems followed the order: wetland > upland farmland > paddy field > forestland. Specifically, the DNRA rate in upland farmland soil was 0.57 ± 0.09 mg N/kg/d. Structural equation modeling indicated that the influence of environmental factors on the soil DNRA rate in subtropical regions decreased in the order: C/$NO_3^-$-N > pH > MAP (Mean Annual Precipitation) > MAT (Mean Annual Temperature) > $NH_4^+$-N. Notably, MAP primarily affected the DNRA rate indirectly by regulating soil pH (Fig.2). Furthermore, we collected typical subtropical lateritic red soils under different crop cultivations to analyze the community characteristics of DNRA bacteria and their correlations with soil environmental factors. The results showed that DNRA bacteria are ubiquitous in Guangxi's lateritic red soils. *Anaeromyxobacter* was the dominant genus within the DNRA bacterial community and was most significantly influenced by C/$NO_3^-$-N and pH (Fig.3).

This research enriches the understanding of microbial nitrogen cycling and provides a theoretical foundation for developing technologies aimed at regulating the DNRA process in subtropical soils to enhance nitrogen use efficiency.

**Table 1. $Na^{15}NO_2$ isotope labeling test of *P.putida* Y-9 and its derivatives**

| Strains | $NO_2^-$ | | $NH_4^+$ | | $^{15}N$ istopic ratios in bacteria (%) | TN (mg/L) | $OD_{600}$ |
|---|---|---|---|---|---|---|---|
| | Content (mg/L) | $^{15}N$ istopic ratios (%) | Content (mg/L) | $^{15}N$ istopic ratios (%) | | | |
| Wild-type strain Y-9 | 44.23 | 13.02 | 0.72 | 5.47 | 2.12 | 83.49 | 0.51 |
| Δ*nirB* | 47.85 | 13.36 | 0.00 | 0.00 | 0.64 | 77.96 | 0.53 |
| Δ*nirB::nirB* | 42.00 | 13.24 | 0.74 | 5.25 | 1.92 | 80.09 | 0.55 |
| Δ*nirD* | 47.54 | 13.39 | 0.00 | 0.00 | 0.72 | 76.04 | 0.46 |
| Δ*nirD::nirD* | 43.38 | 13.11 | 1.41 | 9.41 | 1.77 | 89.23 | 0.50 |



**Fig.1.** Alignment of NirBD among the five strains ("Y-1" represents "*P. plecoglossicida* Y-1"; "Y-9" represents "*P. putida* Y-9"; "Y-11" represents "*P. tolaasii* Y-11"; "J" represents "*P. taiwanensis* J"; "P" represents "*P. putida* P")

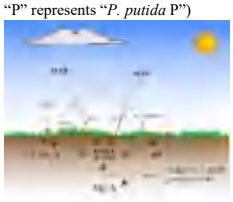


**Fig.2** Environmental factors driving analysis of soil DNRA in subtropical regions

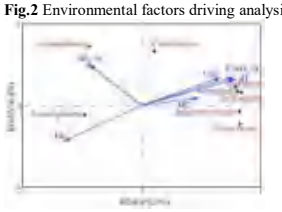


**Fig.3** Redundancy analysis (RDA) of DNRA bacterial community and soil physicochemical factors. Blue arrows represent physicochemical factors, black triangles represent the major bacterial community. The percentage indicates the bacterial community variation explained by each axis. Eh, reduction potential; MC, moisture content; CEC, cation exchange capacity; $NH_4^+$-N, ammoniacal nitrogen

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# Coupled Carbon-Nitrogen Cycles with Global Change

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**ABSTRACT**

The coupled carbon and nitrogen cycles, fundamental to Earth's life-support systems and biogeochemical processes, are increasingly disrupted by global change drivers, with far-reaching implications for the climate system, ecosystems, and human well-being. To support cost-effective global management of these cycles, we developed the Coupled Human and Natural Systems-Carbon and Nitrogen Cycles (CHANS-CN) model, a global-scale framework that quantifies carbon-nitrogen fluxes and examines their interactions across 14 human and natural subsystems while assessing the influences of climate change, human-land interactions, and international trade. Building on this model, we established a cost-benefit analysis framework to evaluate integrated carbon-nitrogen management strategies and introduced a nitrogen credit system designed to incentivize mitigation. Together, the CHANS-CN model, the analytical framework, and the credit system, supported by adaptive policy measures, provide a comprehensive scientific foundation for advancing global food security, environmental protection, and sustainable development through coordinated carbon and nitrogen management.

**Keywords:** Carbon cycle; Nitrogen cycle; Global change; Climate change; Human-land interaction

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# Aligning nitrogen form with rice pReferences raises yield and cuts emissions

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**ABSTRACT**

Rice sustains nearly half of the global population, yet its nitrogen (N) use efficiency remains low, undermining both food security and environmental integrity. Rice predominantly absorbs ammonium ($NH_4^+$), which is readily nitrified and lost through irrigation and drainage, posing a persistent management challenge. Integrating 1,756 paired field observations and global modelling, we show that maintaining soil $NH_4^+$ relative to conventional practices increases rice yield by 6-10% and N use efficiency by 18-33%, while reducing ammonia ($NH_3$) volatilization by 16-50%, nitrous oxide ($N_2O$) emissions by 25-49%, and methane ($CH_4$) emissions by 9-30%. This N transformation-based management could reduce global N fertilizer inputs by 1.4 ± 0.06 million tonnes (Tg), generate an additional 72 ± 13 Tg of rice, and lower $N_2O$, $CH_4$, and $NH_3$ emissions by 0.07 ± 0.02, 6.8 ± 2.0, and 0.6 ± 0.2 Tg, respectively, equivalent to an annual reduction of about 202 Tg $CO_2$-eq. The total social benefit is valued at US$51 ± 5 billion, including US$29 ± 2 billion in added food value, achieved with only US$1.6 ± 0.6 billion in fertilizer investment and US$0.9 ± 0.1 billion in transaction costs. Aligning N transformation processes with crop N pReferences thus represents a pivotal strategy for sustaining rice productivity while minimizing environmental impacts.

**Keywords:** Paddy soil; Rice; Nitrogen use efficiency; Nitrogen budget; Cost-benefit analysis

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# Harnessing soil pore functionality for enhanced nitrogen dynamics understanding and fertilizer management in pastures

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## ABSTRACT

Soil fertility, which involves physical, chemical, and biological processes, is critical in regulating plant nutrient supply. Efficient use of nutrients, such as nitrogen (N), and the minimization of nutrient losses to the environment depend on understanding the interactions between these processes. Effective management requires both temporal correspondence between crop demand and soil supply (*synchrony*) and the appropriate allocation of resources within the root zone (*synlocation*). However, spatiotemporal mismatches often occur between soil supply and plant demand. Consequently, achieving adequate *synchrony* and *synlocation* requires adjusting the N fertilization dose according to the functionality of the pore system. In this context, the objectives of this research are i) to determine the amount and source of mineral N stored within the plant available water porosity volume during the growing season under permanent pasture systems established on volcanic ash soil, and ii) to simulate the transport and storage of mineral N at the matric potentials of PAW (plant available water; ~100 kPa to 60 kPa) in volcanic ash soil.

To achieve these objectives, a four-year field experiment under rainfed conditions in the permanent pasture system will be carried out. Three N doses will be used: i) D1: 180 kg N $ha^{-1}$, ii) D2: 140 kg N $ha^{-1}$, iii) D3: 160 kg N $ha^{-1}$. Additionally, two application strategies will be considered: i) AS1: fertilizer applied at the beginning of the experiment, and ii) AS2: fertilizer applied two weeks after AS1. Urea enriched to 5% atoms in excess of $^{15}N$ will be added to the field experiment (microplot) to determine the movement of N in the soil profile. During the project, continuous soil water content will be measured by field sensors at 20, 40, and 60 cm depth. Soil solution samples will be collected by suction cups placed in the microplot at the studied soil depths to determine nitrate concentration. Sampling of aerial biomass will be collected seasonally. Also, both root exploration and root activity will be simultaneously determined across depths. To describe the characteristic temporal scales of soil water dynamics and related flow processes, the first-year preliminary results will be evaluated using wavelet analysis. Once the wavelet analysis is performed, mineral N data from suction cups and soil water content data at different tensions will be correlated.

These results will provide fundamental knowledge to understand how the soil's dynamic supply allows for both the storage of inorganic N over time and the movement of mineral N from the soil solution toward the roots, functions that are influenced by the soil's hydraulic properties. This understanding will enable us to adjust the nitrogen fertilization dose to efficiently use the available resources while maintaining the productive levels in agroecosystems.

**Key words:** Volcanic soils; Nitrate; Soil water content; Pastures

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# Optimizing water and potassium management enhances yield and water-nutrient use efficiency through improved soil nitrogen availability in citrus orchards

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## ABSTRACT

China is one of the largest producers and consumers of citrus. It is widely cultivated in Southwest China. To maintain a high yield, large amounts of chemical fertilizers are applied in citrus orchards. However, excessive fertilizer application leads to significant nitrogen (N) residue in soils, which is lost through runoff, leaching, ammonia volatilization, and denitrification (Li et al., 2024a). Soil moisture is also the main factor restricting citrus production. Moderate water stress can balance the vegetative growth and reproductive growth of fruit trees (Zhong et al., 2019). However, the citrus production area in Southwest China has been affected by seasonal drought and waterlogging disasters for a long time, which will cause the reduction of soil nutrient utilization and the destruction of the ecological environment (Cui et al., 2024). There are the most abundant microbial communities in soils, which play an important role in soil N cycling (Zhu et al., 2021). According to statistics, terrestrial ecosystems account for about 70% of global $N_2O$ emissions, of which at least 45% can be attributed to microbial N cycling processes (Jones et al., 2014), which is not conducive to farmland ecological balance and plant growth. Therefore, understanding the microbial mechanisms of N cycling under water and fertilizer deficit conditions is crucial for improving soil N availability and promoting citrus production in Southwest China.

Nitrogen is an essential nutrient for plant growth and basal metabolism. Plants' growth depends on available N forms ($NH_4^+$-N and $NO_3^-$-N) (Li et al., 2023). In agricultural ecosystems, the availability of N is a key factor restricting crop yield, which is controlled by the interaction between water-fertilizer management and microbial metabolism. The rhizosphere is a hot spot for nitrification and denitrification, which is different from bulk soils (Wang et al., 2017). Plant roots selectively recruit microbial communities in the rhizosphere, which play an important role in regulating soil N cycling (Schmidt et al., 2019). Soil N cycling is an important part of the biogeochemical cycle, which is mediated by various microorganisms, including N mineralization, N fixation, nitrification, and other redox reactions of various forms of N (Tu et al., 2017). During N fixation, nitrogenase, encoded by *nifH*, fixes atmospheric $N_2$ into a biologically usable form. Ammonia monooxygenase (AMO) is encoded by *amoABC* genes in ammonia-oxidizing bacteria (AOB) or archaea (AOA) (Shang et al., 2023). They catalyze the transformation of $NH_3$/$NH_4^+$ to $NH_2OH$ (Liu et al., 2023). Nitrite reduction in plants can stimulate $N_2O$ emission, which is mainly driven by Proteobacteria (Hou et al., 2019). Denitrification genes include nitrate reductase (*narG*), nitrite reductase (*nirS* and *nirK*), and nitrous oxide reductase (*nosZ*) (Nadeau et al., 2019). Among these, *nirS* and *nirK* catalyze the reduction of $NO_2^-$ to NO, and they are usually used as marker genes for denitrification (Ming et al., 2024). In addition, $NO_3^-$ may be reduced through other metabolic processes, including dissimilatory nitrate reduction (DNRA) and assimilatory nitrate reduction (ANRA) (Broman et al., 2021).

Water affects plant growth and biogeochemical cycles of all elements in terrestrial ecosystems. Soil N cycling is particularly sensitive to water availability. Extreme droughts significantly impact the pools, fluxes, and processes of terrestrial N cycling, leading to decreases in N mineralization and nitrification (Deng et al., 2021). However, excessive irrigation can accelerate microbial N turnover, increasing the potential for nitrate leaching and gaseous N emissions (He et al., 2022). Potassium (K) is a major osmotic regulator, enhancing the water uptake ability of plants under drought stress, which plays an important role in the transport of photosynthetic products, nutrient metabolism and physiological growth of fruit (Zhang et al., 2019). It is conducive to nutrient uptake, yield, and quality improvement of citrus fruit. Moderate K application also increased N use efficiency by interacting with $NH_4^+$ in soils and significantly affecting N transformation processes (Li et al., 2020). Moreover, the appropriate K fertilizer application also increased the diversity of bacterial community in soils, which can indirectly increase citrus fruit yield by regulating rhizosphere soil enzyme activity, organic matter, and N cycling (Li et al., 2023).

Water and f K fertilizer deficit regulation with drip irrigation ($WKDR_{DI}$) is a new technology that accurately and evenly transports water and nutrients to the plant root zone. It can create a moderate water and nutrient deficit environment during the key growth stages of citrus, stimulate the physiological adaptability of citrus trees, and regulate the rhizosphere microenvironment. However, systematic research on N cycling and the microbial mechanisms in citrus rhizosphere soils under $WKDR_{DI}$ is still underexplored. Therefore, in this study, a control treatment (CK) with full irrigation and fertilization, two degrees of water deficit treatments (20% and 40%), and three degrees of K fertilizer deficit treatments (20%, 40% and 60%) were set up at fruit expansion stage (stage III, early July to late October) and fruit maturation stage (stage IV, early November to late February), respectively. The specific treatment included 20% water deficit and 20% K deficit (HWHK), 20% water deficit and 40% K deficit (HWMK), 20% water deficit and 60% K deficit (HWLK), 40% water deficit and 20% K deficit (LWHK), 40% water deficit and 40% K deficit (LWMK), and 40% water deficit and 60% K deficit (LWLK). This study aims to: (1) clarify the effectiveness of soil inorganic N components under $WKDR_{DI}$ at fruit expansion and maturation stages; (2) reveal the abundance of N cycling functional genes and microbial communities under $WKDR_{DI}$ at fruit expansion and maturation stages; (3) explore the effect of soil inorganic N availability and rhizosphere microenvironment on citrus production under $WKDR_{DI}$.

Results showed that **$WKDR_{DI}$ improved soil ammonium availability by promoting the N fixation process and reducing denitrifiers at the citrus fruit expansion stage (stage III).** The fruit expansion stage (stage III) is crucial for fruit rapid growth and dry matter accumulation. Since N is the main component of protein, nucleic acid, and chlorophyll (Wang et al., 2024), the demand for N in citrus fruits increased at this stage, and the metabolism and transport of N in rhizosphere soils also increased simultaneously. Our study found soil $NH_4^+$-N and total inorganic N contents increased significantly under the III-HWHK treatment, which was significantly affected by the degree of water deficit. At the same time, the III-HWHK treatment can promote the N fixation process and related genes (*nifD* and *nifK*), which were significantly affected by the degree of water deficit. This treatment also inhibited denitrification by reducing the abundance of denitrification genes (*nirK*, *norB*, *norC,* and *nosZ*). Additionally, *Ochrobactrum*, *Rhizobium,* and *Achromobacter* were the main denitrifiers carrying *nirK* and *norB* genes, and their relative abundance decreased significantly under the III-HWHK treatment. This may be the main reason for inhibiting denitrification and promoting soil ammonium availability. On one hand, moderate irrigation was beneficial to soil permeability and decreased the relative abundance of *nirS*-type and *nirK*-type denitrifiers (Zhang et al., 2021), thus inhibiting denitrification. On the other hand, Moderate K fertilizer is beneficial for creating eutrophic environments in soils and significantly affects bacterial and fungal taxa essential for organic matter decomposition (Li et al., 2024b), thereby balancing the composition and content of available N in soils. Therefore, the III-HWHK treatment can effectively improve soil ammonium availability by promoting N fixation and increasing the relative abundance of related genes (*nifD* and *nifK*). The abundance of denitrification genes (*nirK*, *norB,* and *nosZ*) and denitrifying microbial communities (*Bradyrhizobium*, *Stenotrophomonas,* and *Cupriavidus*) at stage III were significantly reduced under this treatment, thereby inhibiting the soil denitrification process, and also improving ammonium availability.

**$WKDR_{DI}$ also improved soil nitrate availability by increasing the abundance of nitrifiers at the citrus fruit maturation stage (stage IV).** Citrus prefers nitrate during growth, the increase in soil nitrate availability is beneficial to citrus growth. In this study, soil $NO_3^-$-N content increased significantly under the IV-HWMK treatment. This may be due to soil nitrification process being significantly promoted under this treatment. Moderate water deficit created an aerobic environment conducive to nitrifiers in soils, facilitating the nitrification process (Bozal-Leorri et al., 2023). In addition, although $NO_3^-$-N is negatively charged and adsorbed on soil particles, it has strong mobility and migrates with water flow (Xiao et al., 2019), so that moderate water deficit can reduce the nitrate leaching to deeper soil layers while increasing nitrate availability in the upper soil (Chen et al., 2024). The relative abundances of *amoA*, *amoB*, *amoC,* and *hao* genes also showed an increasing trend under $WKDR_{DI}$, with the IV-HWMK treatment showing the most significant increase. The main reason is that AOA and AOB are sensitive to soil moisture and oxygen conditions (Yang et al., 2018). The change of soil moisture directly affects the abundance of ammonia oxidizing microorganisms. Moderate water deficit drove the activity of AOA and AOB, thus increasing the abundance of related genes and promoting nitrification. Importantly, moderate irrigation and K fertilizer application were beneficial to soil N mineralization, providing additional $NH_4^+$-N in soils (Barra et al., 2023). The increase of soil $NH_4^+$-N content will stimulate the reproduction of nitrifying microorganisms, increasing the abundance of nitrifying genes and promoting nitrification (Liu et al., 2024), and improving soil nitrate availability. In particular, we also found the relative abundance of *Nitrosocosmicus* carrying the *amoC* gene was significantly increased under the IV-HWMK treatment, which directly promoted the enhancement of nitrification, thus effectively improving the effectiveness of nitrate in citrus rhizosphere soils. Therefore, the IV-HWMK treatment could promote nitrification by increasing the abundance of the *amoC* gene and nitrifying microbial communities (*Cupriavidus*, *Streptomyces*, *Nitrosospira,* and *Nitrosocosmicus*), which were the main reasons for the improvement of soil nitrate availability.

Moreover, **$WKDR_{DI}$ promoted citrus production by improving rhizosphere microenvironment and soil nitrogen availability.** Soil microenvironment is regulated by rhizosphere microorganisms, which can directly or indirectly affect the growth and development of plants. Soil moisture and nutrient availability significantly affect N cycling by altering the metabolic activity of soil microorganisms (Shang et al., 2023). The treatment of III-HWHK and IV-HWMK significantly improved citrus yield characteristics, including yield, partial factor productivity from nitrogen ($PFP_N$), partial factor productivity from potassium ($PFP_K$), and irrigation water productivity ($WP_I$). These were achieved by increasing soil inorganic N availability. The main reason is that the increase in soil inorganic N availability can promote the accumulation of amino acid proline, promote cell division and expansion during fruit development, and facilitate the storage of N and carbon in fruits (de Carvalh et al., 2024). It also promotes the transfer of more available N to leaves, enhances photosynthesis, and continues to provide carbohydrates for the fruit (Chen et al., 2023). In addition, moderate water and K deficiency can accurately regulate the level of water and $K^+$ in soils, and promote the transfer of $K^+$ absorbed by citrus roots to fruits (Li et al., 2024c), and promote the sugar and acid metabolism in citrus fruits (Cui et al., 2024). Meanwhile, it also balances the osmotic concentration between the rhizosphere and root cells, which is conducive to the absorption and utilization of water by plants (Cui et al., 2023). Above all, the increase in inorganic N availability in soils under $WKDR_{DI}$ optimized fruit yield characteristics by regulating the synthesis of photosynthetic products, nutrient transport and distribution, and its adaptability to water stress in citrus fruits.

In summary, the treatment of III-HWHK and IV-HWMK at the key growth stages of citrus fruits can regulate rhizosphere N cycling microorganisms, increase fruit yield, and improve the water and nutrient use efficiency. These findings will enhance our understanding of the responses of N cycling in citrus rhizosphere soils to $WKDR_{DI}$, and provide a theoretical basis for the formulation of the best irrigation and K fertilizer regulation strategies in citrus production in Southwest China.

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# Depth-Dependent Soil Compaction as a Modulator of Nitrous Oxide Fluxes in Cropping Systems

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## ABSTRACT

Agricultural soils are major sources of nitrous oxide ($N_2O$) emissions, primarily produced through denitrification and nitrification. However, the impact of soil compaction on $N_2O$ emissions remains debated. To address this, a two-year lysimeter experiment was conducted under five different cultivation systems with four replicates each: bare soil (BS), conventional agriculture (CV), conventional agriculture + cover crop (CC), conservation agriculture with shallow soil compaction (0-25 cm, CA1), and conservation agriculture with deep soil compaction (25-45 cm, CA2). Grain sorghum was grown in 2023, maize in 2024, and annual ryegrass served as the cover crop. Main crops received solid digestate fertilization at 300 kg $ha^{-1}$ annually. Continuous automatic measurements of $N_2O$ emissions were monitored using a non-steady state through-flow chamber system coupled with an FTIR gas analyzer, capturing up to seven flux measurements per chamber per day. Daily emissions were analyzed in four periods: post-fertilization, main crop growth, post-harvest, and cover crop growth. Concurrent measurements of NOx, water-filled pore space (WFPS; 0-15 cm) and soil temperature (0-30 cm) helped contextualize emission dynamics. Additionally, 280 soil samples were collected in each year within the 30 days following fertilization from 0-5 cm and 5-15 cm depths to analyze pH, ammonium ($NH_4$-N), nitrate ($NO_3$-N), and nitrite ($NO_2$-N) dynamics. $NH_4$-N concentrations peaked within three days following fertilization then declined rapidly, while $NO_3$-N concentration peaks were generally observed fourteen days after fertilization. Across all years, peak $N_2O$ emissions occurred within two weeks post-fertilization, with the highest emissions observed in CC in 2023 (1.02 kg $ha^{-1}$) and in CV in 2024 (5.15 kg $ha^{-1}$). The lowest emissions consistently appeared in CA2 (0.35 kg $ha^{-1}$ in 2023 and 1.24 kg $ha^{-1}$ in 2024). These results were also confirmed when considering the overall two-year period, underscoring the critical role of soil structure and cultivation methods in mitigating $N_2O$ emissions.

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# Evaluating the Fate of Nitrate in Deep Soils Using Dual Isotopes

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**ABSTRACT**

Nitrogen (N) fertilizer use in agriculture significantly increases food supply at the expense of environmental degradation, such as nitrate ($NO_3^-$) leaching into ground water and nitrous oxide ($N_2O$) emissions as greenhouse gas (GHG) aggravating global warming. However, how land use and management influence the N dynamics in the soil profile and the fate of $NO_3^-$ in the system still remain unknown. To find the best mangement practice that can reduce nitrogen loss into the environment, we measured the concentration of $NO_3^-$ and its stable isotope abundance ($^{15}N$ and $^{18}O$), together with the potential denitrification rate across a four-foot (122 cm) soil profile under various cropping systems receiving cover crops, no-till, manure, organic, and pasture. Currently, we found dairy forage systems generally exhibit higher total denitrification rates to reduce $NO_3^-$ leaching risk compared to cash grain systems, while organic systems can significantly reduce $N_2O$ production in surface soils compared to other systems. The organic dairy forage system shows the most potential for nitrate attenuation, with the lowest associated cost of $N_2O$ emissions. Along with other environmental factors, we try to develop a mechanistic understanding of how land use and management regulate N cycling processes, providing more accurate estimates of cost efficiency in utilizing best management practices to meet agricultural and environmental goals.

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# Climate change effects on nitrogen cycles in global grasslands

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**ABSTRACT**

Grasslands, as one of Earth's major ecosystems, are critical for sustaining biodiversity, ecosystem services, and global food security. However, their nitrogen cycles are increasingly influenced by climate change, including elevated atmospheric $CO_2$ ($eCO_2$), warming, and shifting precipitation regimes. These changes significantly affect grassland productivity and nitrogen dynamics, with substantial regional variations. Using a synthesis of over 5,000 experimental observations coupled with multiple ecosystem models, we investigated the impacts of climate drivers on nitrogen dynamics under the SSP2-4.5 scenario. Elevated $CO_2$ alone is projected to enhance global grassland net primary productivity (NPP) by 10% while reducing leaf nitrogen content by 8%, resulting in a net increase of 4 Tg $yr^{-1}$ increase in nitrogen harvest by 2050. Enhanced nitrogen use efficiency (+29%) and biological nitrogen fixation (+66%) under $eCO_2$ would reduce nitrogen surplus (-29 Tg $yr^{-1}$) and fertilizer demand (-9 Tg $yr^{-1}$), potentially mitigating nitrogen pollution and yielding economic benefits of 235 billion USD. Warming, as another driver, is projected to increase nitrogen inputs by 17 Tg $yr^{-1}$ and nitrogen harvest by 12 Tg $yr^{-1}$ but may exacerbate reactive nitrogen losses by 5 Tg $yr^{-1}$. Adaptation measures to minimize nitrogen leakage could deliver economic gains of 121 billion USD by 2050. Precipitation shifts further complicate nitrogen dynamics. Regions with increased precipitation, such as the United States and mid-to-high latitude Asia, could see nitrogen harvest rise by 16 Tg $yr^{-1}$, while areas facing reduced precipitation, including Sub-Saharan Africa and South Asia, risk a 9 Tg $yr^{-1}$ harvest decline. These imbalances could worsen global inequalities in nitrogen cycles and food security. Our findings highlight the need for improved representation of these complex interactions in ecosystem models to guide climate adaptation strategies. Timely, targeted interventions can help balance benefits and risks, safeguard ecosystem health, and support sustainable, equitable grassland management in a changing climate.

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# Flooding duration and temperature jointly drive soil nitrogen transformation rates in the floodplain wetlands of Poyang Lake during the dry season

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## ABSTRACT

Drought and human activities pose substantial threats to wetland ecosystems. As the largest wetland in Asia, its ecological process has been significantly affected by hydrological dynamics. While the nitrogen (N) cycle is one of the key components in wetland ecosystems; however, the Poyang Lake Wetland has received limited attention regarding how flooding duration during the dry season affects soil N transformation rates. Therefore, this study therefore focused on the Poyang Lake Wetland in the dry season to explore the impacts of flooding duration and temperature on soil N transformation rates, and to clarify the regulatory roles of soil physicochemical properties, enzyme activities, and microbial functional gene abundances. Fieldwork was conducted from January to March in 2021, and, five plant community transects were established along a natural flooding gradient with different dominant species: *Artemisia selengensis* community, *Phalaris arundinacea* community, *Carex cinerascens* community, *Eleocharis congesta* community, and mudflat. Field situ incubation experiments were carried out, and samples were taken to measure the soil and microorganisms. Analysis of variance, correlation analysis, and regression analysis were employed to discuss the relationships between flooding duration, temperature, and N transformation rates. Results showed that: 1) Prolonged flooding duration significantly elevated net N ammonification and mineralization rates, though its effect on net nitrification varied across months. 2) Flooding duration significantly increased soil moisture and pH, while ammonium and total inorganic N contents exhibited a pattern of initial increase followed by decline with prolonged flooding, with nitrate responses showing monthly variability. 3) Protease and urease activities decreased markedly with extended flooding duration, whereas N-acetyl-β-D-glucosaminidase activity and N gene abundances related to N transformation remained virtually unchanged. 4) This study demonstrates that the impacts of flooding duration and temperature on N transformations were primarily driven by shifts in soil physicochemical properties, with enzyme activities and microbial genes making very limit contributions. These findings had significant implications for the management and conservation of the Poyang Lake Wetland Ecosystem.

# Identifying the driving factors of soil nitrate nitrogen via MLs-GIS framework in an intensive plain agricultural area, China

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## ABSTRACT

Excessive accumulation of nitrate nitrogen (*SNN*) in soil is a global ecological issue, with adverse effects on terrestrial and aquatic ecosystems, particularly in developed planting-breeding mixed areas with multiple sources and high input of nitrogen. Here, a total of 251 topsoil samples were collected from a typical agricultural planting area on the North China Plain, China. At the same time, a multisource data including N-fertilizer types and input, physicochemical properties of soil, topographic factors, spatial distance factors, land use and land cover, remote sensing factors, were constructed. Then, a framework combining machine learning models with spatial analysis by GIS (MLs-GIS) was built to clarify the fit of the spatial distribution and identify key factors influencing *SNN*. The results revealed that the content of *SNN* at different sites varied significantly (from 0.02 to 58.85 mg/kg). The *soil pH* ranged from 5.18 to 8.69, with an average value of 8.12. Field investigations revealed that the primary type of N fertilizer was ternary compound fertilizer followed by urea. Correlation analysis showed *soil pH* was significantly negative correlated with *SNN* ($p < 0.01$), but not significant for *chemical N fertilizer input* though a positive correlation relationship. According to the performance of the ML models, namely, the random forest (RF), GBDT, LightGBM and XGBoost, *soil pH* and *chemical N fertilizer input* were the main factors influencing *SNN*. The RF model exhibited the best performance, with the highest prediction accuracy ($R^2$ =0.64), and warrants increased attention in the management of agricultural nitrogen pollution. In summary, the MLs-GIS framework is efficient at identifying the key influencing factors and the spatial distribution of *SNN*. While, an existing limitation of the study is the insufficient incorporation of soil physicochemical properties, which may reduce the predictive performance of the models. These critical factors are closely related to the SNN content, such as the soil texture and soil bulk density, and should be included in model analysis in future steps.

**Acknowledgments**

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# Patterns and mitigation mechanisms of dinitrogen emissions and ammonia volatilization from paddy under elevated $CO_2$ and warming

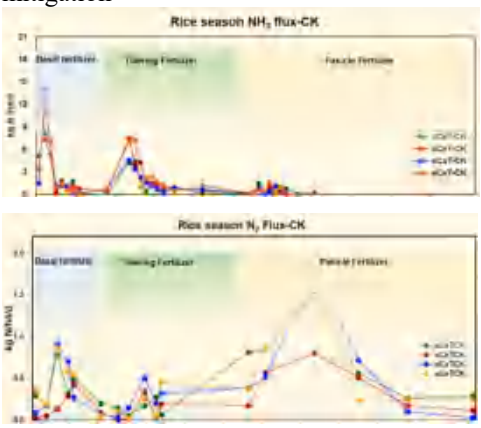
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## ABSTRACT

The impacts of elevated carbon dioxide ($eCO_2$) and warming on plant growth and soil nitrogen metabolism are complex, particularly as their interaction can present additive, synergistic, or antagonistic effects on different parameters. Dinitrogen ($N_2$) emission and ammonia ($NH_3$) volatilization represent major pathways of nitrogen loss in paddy fields. However, the responses of these two gaseous losses to the interaction between $eCO_2$ and warming, along with the relative contributions of soil-derived versus fertilizer-derived nitrogen remained a significant knowledge gap, undoubtedly poses a challenge for formulating effective nitrogen mitigation strategies under climate change scenarios. Our study addressed this by utilizing a Temperature and Free-Air $CO_2$ Enrichment (T-FACE) platform, integrated with a Membrane Inlet Mass Spectrometer (MIMS) enabling for the first time the in-situ observation of $N_2$ emission patterns in paddy under $eCO_2$ and warming while simultaneously monitoring $NH_3$ volatilization losses. Furthermore, we employed $^{15}N$-labeled urea to differentiate the contributions of native soil nitrogen and applied fertilizer to both $N_2$ emissions and $NH_3$ volatilization under simulated climate change. Additionally, we evaluated the mitigation efficacy of two conventional measures—biochar and nitrification inhibitors (DMPP) under these future climate scenarios. Through continuous monitoring over two rice growing seasons, our research revealed that $eCO_2$ alone stimulated $N_2$ emissions whereas warming alone suppressed it. Under the interaction, warming mitigated the promotional effect of $eCO_2$ on $N_2$ emissions. Conversely, $eCO_2$ alone inhibited $NH_3$ volatilization while warming alone promoted it. Their interaction revealed that $eCO_2$ alleviated the stimulatory effect of warming on $NH_3$ volatilization. Although the individual effects of $eCO_2$ and warming on $N_2$ and $NH_3$ were opposing, their combination ultimately led to an increase in the cumulative losses of both gases. Analysis across fertilization stages (basal, tillering, panicle) revealed a distinct trade-off: $NH_3$ volatilization decreased while $N_2$ emissions increased from the basal to the panicle stage. Under climate change, $NH_3$ volatilization primarily originated from the fertilizer. In contrast, the contribution of soil versus fertilizer to $N_2$ emissions was temperature-dependent: under $eCO_2$ without warming, the soil was the primary source of $N_2$, whereas under warming conditions, fertilizer became the major contributor. For mitigation, the DMPP was significantly superior to biochar in reducing the cumulative total of $N_2$ and $NH_3$ losses, primarily due to its substantial reduction of $N_2$ emissions. In conclusion, our research not only fills a critical international knowledge gap regarding in-situ $N_2$ losses from paddy under future climate scenarios but also provides a theoretical foundation for developing adaptive nitrogen management strategies to mitigate nitrogen losses in a changing climate.

**Keywords:** Climate change interaction; Dinitrogen ($N_2$) emissions; Soil and fertilizer source; $^{15}N$-labeled urea; Nitrogen mitigation



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# Mitigation and Synergistic Effects of Management Practices on Pollution Reduction, Carbon Sequestration, and Emission Reduction in Sloping Farmland: A Meta-Analysis

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**ABSTRACT**

Sloping farmland is a critical global agricultural resource for ensuring food security, but its topographic features (particularly slope) make it a hotspot for greenhouse gas (GHG) emissions ($CO_2$, $CH_4$, $N_2O$) and nitrogen pollution (e.g., leaching, runoff, and ammonia volatilization), posing significant ecological threats. Achieving green and sustainable development in these systems requires a systematic understanding and synergistic regulation of carbon and nitrogen cycles to maintain crop productivity while minimizing environmental impacts.

This study conducted a meta-analysis to integrate field experimental data from published studies worldwide, quantitatively evaluating the effects of management practices (e.g., conventional tillage, conservation tillage, optimized fertilization, terracing, cover crops, and biochar application) on GHG emissions, nitrogen loss, and crop productivity under varying slope conditions. Through rigorous literature screening, 535 independent cases were included to build a comprehensive database incorporating slope, management types, environmental variables (e.g., GHG fluxes, nitrogen loss, yield), and background factors (e.g., soil type, climate, crop species). Using random-effects models, effect sizes (e.g., response ratio, standardized mean difference) were calculated for key indicators. Subgroup analysis and meta-regression revealed interactions between slope and management practices, highlighting carbon-nitrogen synergy mechanisms. The results provide a scientific basis for optimizing region-specific management strategies to enhance pollution control, carbon sequestration, and emission reductions in sloping farmland systems.

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# Feasibility of gypsum by-products as soil amendment to mitigate nitrous oxide emission from arable soil

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**ABSTRACT**

Sulfate ($SO_4^{2-}$) can act as alternative electron acceptors under anaerobic soil conditions, potentially suppressing nitrous oxide ($N_2O$) production by competing with nitrate ($NO_3^-$) during microbial respiration. The objectives of this study were 1) to evaluate the feasibility of $SO_4^{2-}$-containing industrial by-products as soil amendment to mitigate $N_2O$ emissions from arable soils and 2) to determine the most effective amendment. An incubation experiment was conducted using both soil orders, Inceptisol and Andisol. Ninety grams of air-dried soils were mixed with neutralized gypsum ($CaSO_4 \cdot 2H_2O$), phosphogypsum ($CaSO_4 \cdot CaHPO_4$), and calcium sulfate ($CaSO_4$) at a rate of 1% (*wt/wt*) and 1 g of urea fertilizer was added as a nitrogen source. Soil mixtures were incubated at 25°C for 4 weeks under controlled moisture conditions with water-filled pore space (WFPS) set at 30%, 60%, 90%, and 100% to simulate various soil moisture regimes. Daily $N_2O$ fluxes increased over time in all treatments with a remarkable peak observed approximately two weeks later, indicating a delayed microbial activity related to nitrogen transformations and $SO_4^{2-}$ utilization. Cumulative $N_2O$ emissions were significantly lower with $SO_4^{2-}$-amended soils compared to the control across all WFPS levels. Calcium sulfate showed the greatest mitigation effect, followed by neutralized gypsum and phosphogypsum. The mitigating effect of $SO_4^{2-}$ was attributed to its role as an alternative electron acceptor that inhibited denitrification or competed with $NO_3^-$ reduction, and an inverse relationship was observed between soil $NO_3^-$ concentrations and cumulative $N_2O$ emissions. Particularly in $SO_4^{2-}$ -treated soils, consistently higher $SO_4^{2-}$ levels were maintained throughout the incubation. This suggested that $SO_4^{2-}$ redirected microbial respiration away from $NO_3^-$ reduction, thereby reducing $N_2O$ production. Nitrous oxide emissions decreased with increasing WFPS in both soil orders, showing the greatest emissions at 30% WFPS and the least at 100%. At higher WFPS, residual $SO_4^{2-}$ concentrations declined, indicating enhanced microbial $SO_4^{2-}$ reduction under anaerobic conditions. Overall, these findings demonstrate that $SO_4^{2-}$ amendments, specifically industrial by-products such as phosphogypsum and neutralized gypsum, possess strong potential for $N_2O$ mitigation and sustainable resource recycling. Although calcium sulfate showed a slightly greater reduction in $N_2O$ emissions, both phosphogypsum and neutralized gypsum clearly reduced emissions compared to the control and exhibited comparable mitigation effects to each other. In addition, these gypsum by-products offer advantages in terms of cost-effectiveness and environmental sustainability, especially in Andisol, making them promising soil amendments for field application.

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# Summer fallow drives leaching of legacy nitrogen in cereal land converted from old orchard

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## ABSTRACT

Understanding the fate of high nitrate accumulated in soil profiles (legacy nitrogen; LN) of cereal lands converted from intensive orchards (OC) is important for N management and environmental protection. This study has quantified changes in water and nitrate contents in soil profiles after OC during summer fallow on the southern Loess Plateau. HYDRUS-1D model was used to simulate the changes of water and N in soil profiles. The results show that summer fallow significantly increased the total water storage in the 0–500 cm soil profile of the OC treatment. Water recovery reached to the depth of 440 cm after the fallow. The scenario analysis of different precipitation patterns revealed a significant correlation between LN leaching and precipitation patterns. The leaching of LN in the soil layers at 200–300, 300–400, and 400–500 cm was estimated to be 390, 297, and 113 kg N $ha^{-1}$, respectively. The model predicted that recovery depths of soil water content at the average precipitation scenario during the summer fallow after 10 years of OC reaches up to a depth of 15 m; the peak depth of LN after 15 years of OC can reach up to 10 m. It highlights that while converting old orchards to cereal land improves soil water recovery during summer fallow, it simultaneously increases N leaching into the deep soil profile, which diminishes crop-available nitrogen. Balancing the trade-off between soil water recovery and legacy nitrate leaching into deeper soil is a challenge.

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# Integrated Modelling and Technological Tools to prevent Agricultural Non-Point Source Nitrate Pollution of Shallow Groundwater in Arborea Area, Sardinia, Italy

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## ABSTRACT

Agricultural activities, especially those with poorly managed irrigation, synthetic fertilizers and livestock manure, are major contributors to soil and groundwater pollution, mainly by $NO_3$. To address this, the European Union introduced the $NO_3$ Directive (91/676/EEC) in 1991 requiring monitoring, designation of $NO_3$ Vulnerable Zones, NVZs, and the adoption of good agricultural practices and action plans to prevent and reduce $NO_3$ Non-Point Source, NPS, pollution. Despite these measures, $NO_3$ levels in shallow groundwater remain high in Arborea area on Sardinia Island's west coast, Italy, with monitoring data showing an upward trend. The NVZ in the sandy Arborea Plain faces excessive nitrogen input due to intensive livestock and agriculture. This study aims to mitigate agricultural NPS $NO_3$ pollution by integrating Site-Specific Best Management Practices, SSBMPs, and cost-effective field-scale bioreactors, BRs, to attenuate and intercept $NO_3$ pollution. Three pilot fields were selected in Arborea. Soil, vegetation, groundwater, irrigation and fertilization data were collected from each of pilot fields. FLOWS physically-based agrohydrological model was used to: 1) evaluate and quantify the water and $NO_3$ leaching to the groundwater under current practices, and 2) optimize irrigation water to minimize $NO_3$ leaching. In each of the three pilot fields, an artificial subsurface drainage network was installed to collect the percolation fluxes and transport them to a bioreactor specifically installed for this study. The BRs were designed to treat drainage water anoxically to remove $NO_3$ in the porous medium made by filling an excavated pit (25 × 4 × 1.2 m) with eucalyptus woodchips. Inlet and outlet structures along with a monitoring system were installed in each BR to monitor water quality parameters, to collect water samples at the inlet and outlet and to control the hydraulic gradient to sustain an average residence time of 4 to 6 h. Laboratory analyses illustrated high BR performance, reaching 100% of $NO_3$ removal rates in two of the pilot BR and 89% in one. The three BR effectively treated 1222, 2929 and 1830 kg of $NO_3$ over the period of 4 months between June 1st and September 30th, 2025. The collected data were used as inputs to FLOWS model whose results showed significant potential reduction in water and $NO_3$ fluxes to groundwater by optimizing irrigation water or by supplying the daily evapotranspiration demand.

**Acknowledgments**

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# Short-term intercropping reduces symbiotic nitrogen fixation and alters the proportion of nitrogen pool derived from soil free-living nitrogen fixation

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**ABSTRACT**

Biological nitrogen fixation (BNF), primarily mediated by symbiotic (SNF) and free-living (FLN) diazotrophs, constitutes a critical source of bioavailable nitrogen in agricultural systems. However, their simultaneous responses to intercropping remain poorly understood. Here, we simultaneously investigated the responses of SNF by Chinese milk vetch (*Astragalus sinicus* L.) and soil FLN to intercropping with silage maize (*Zea mays* L.), alongside analyses of soil N pools and microbial communities. Intercropping reduced the proportion of atmospheric $N_2$ fixed by milk vetch (Ndfa) but increased the dry matter yield of silage maize. While the total rate of soil FLN remained unchanged, intercropping significantly altered the partitioning of fixed N among key soil N pools: the organic, inorganic ($NH_4^+$ and $NO_3^-$), and microbial biomass N pools. Specifically, the rhizosphere of milk vetch exhibited an increase in microbial biomass N derived from FLN, whereas that of silage maize showed enhanced $NO_3^-$-N from FLN. These shifts occurred without major changes in bulk soil properties but were concomitant with distinct restructuring of the fungal, bacterial, and diazotrophic communities. Notably, the abundance of specific dominant diazotrophs (e.g., *Sinorhizobium*, *Bradyrhizobium*), bacteria (*Microvirga*, *Bacillus*), and fungi (e.g., *Fungi_gen_Incertae_sedis*) was positively correlated with the proportion of inorganic N derived from FLN. Our findings demonstrate that milk vetch-maize intercropping enhances N bioavailability from FLN in a plant-specific manner, offering a promising strategy to benefit silage maize productivity.

**Keywords:** interspecific facilitation, green manure, diazotrophic community, rhizosphere microbiome, bioavailable nitrogen, plant-bacteria interaction

**Acknowledgments**

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# Balancing Productivity, Profitability, and Sustainability: Quantifying Nitrogen Fate and Optimizing Site-Specific Management in High-Rainfall Agroecosystems

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## ABSTRACT

In the humid southeastern US, winter wheat (*Triticum aestivum* L.) production faces a critical dual challenge: heavy winter rainfall (>900 mm) creates high-risk conditions for nitrogen (N) leaching, while rising input costs impede farm profitability. Current management practices often rely on fall-applied poultry litter (PL), yet a critical knowledge gap exists regarding the fate of this unaccounted-for N and the optimal strategies to mitigate N losses. This study integrated field-based N budgeting, process-based modeling (DSSAT-CERES-Wheat), and multi-criteria decision analysis (AHP-TOPSIS) to quantify the fate of unaccounted-for N through different loss pathways and identify regulatory management strategies that balance farm profitability with environmental sustainability. Using two years of field data and 32 years of historical climate simulations across contrasting yield zones (High-Yielding Zone [HYZ] and Low-Yielding Zone [LYZ]), we first quantified the stochasticity of N loss pathways. Field-calculated budget revealed substantial "unaccounted-for N" (90-160 kg[N] $ha^{-1}$), which model simulations validated was primarily driven by nitrate leaching (69±21 kg[N] $ha^{-1}$). These losses were highly dynamic and peaked in wet years (96±21 kg[N] $ha^{-1}$) and significantly exceeded volatilization (1.6±0.5 kg[N] $ha^{-1}$) and denitrification (0.7±0.2 kg[N] $ha^{-1}$). Across both yield zones, the dominant driver of N losses was the asynchrony between fall mineralization and crop uptake. We subsequently evaluated planting dates and N management strategies to mitigate these losses. Delaying planting from mid-October to late November reduced crop N uptake and increased leaching by 18-21%. Although the farmer's baseline practice (T1: 130 kg[N] $ha^{-1}$ UAN + 5 Mg $ha^{-1}$ PL-Fall) maximized yield, it was economically inefficient and amplified N loss risk. In contrast, the AHP-TOPSIS analysis revealed that transitioning to a split-application of UAN only (130 kg[N] $ha^{-1}$) reduced environmental N losses by 4-8 kg[N] $ha^{-1}$ while increasing net returns by 36-70% across both zones. This strategy rectified the supply-demand asynchrony without compromising yield stability. These findings demonstrate that soil N fate in winter wheat is governed by climate-driven hydrologic fluxes and management timings. The integrated DSSAT-AHP-TOPSIS framework provides a transferable approach for regulating N losses, informing policies on organic amendment timing, and guiding climate-smart, site-specific nitrogen management in high-rainfall agroecosystems.

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# Regenerative Management Reduces Nitrous Oxide Emissions from Dairy Pastures

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## ABSTRACT

Nitrous oxide ($N_2O$) emissions from ruminant urine patches are a major source of greenhouse gases in grazed pasture systems. Regenerative agriculture (RA) has gained global attention for its potential to improve environmental sustainability compared with conventional agriculture (CA), yet field evidence of its effect on $N_2O$ emissions remains limited. This study compared $N_2O$ emissions from synthetic cow urine patches on two adjacent dairy farms in New Zealand, one managed under CA and the other under RA practices. The comparison considered two soil histories present on both farms, reflecting the time since conversion from forestry to pasture: 23 years for early-converted soils and 9 years for late-converted soils. Plot pairs representing early- and late-converted soils were established in four paddocks on each farm, and $N_2O$ emissions were monitored over 71 days using the static closed chamber method.

Our results showed that cumulative $N_2O$ emissions were 72% lower in regenerative pastures compared with conventional pastures, demonstrating a substantial mitigation potential under regenerative management. Soil history strongly influenced emission patterns within each farm. At the CA site, urine-induced emissions were 152% higher from early converted soil than late converted soil ($p < 0.001$), whereas at the RA site, late converted soil produced 223% higher emissions than early converted soil ($p < 0.001$). Emission factors reflected these trends, with the highest in early converted CA soil ($0.61\% \pm 0.42$) and the lowest in early converted RA soil ($0.04\% \pm 0.03$).

These findings provide field-based evidence that RA practices can substantially mitigate $N_2O$ emissions from pasture soils while maintaining productivity, highlighting their potential role in sustainable dairy farming systems.

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# Evaluation of nitrogen mineralization characteristics of paste fertilizer in Japanese paddy soils

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## ABSTRACT

Paste fertilizer, a type of controlled-release fertilizer, is a high-concentration liquid compound fertilizer with a certain level of viscosity. It has gained attention because, unlike coated fertilizers that use plastic shells, it does not generate microplastics. However, no studies have investigated the temperature dependence of nitrogen mineralization from paste fertilizer. This study aimed to clarify the nitrogen mineralization rate and temperature dependency of paste fertilizer through kinetic analysis and to compare its behavior with conventional urea solution. A 12-week laboratory incubation experiment was conducted using three paddy soils from northeastern Japan: two Inceptisols (Yamagata and Aomori Prefectures) and one Andosol (Iwate Prefecture). Incubations were performed under flooded conditions at three temperatures (10°C, 20°C, and 30°C). 10-g subsamples soil (on an oven-dried basis) were weighted into 68-mL serum bottles with 9.6mg N addition and flooded by 10ml water. After 0, 7, 14, 28, 56, and 84 days of incubation, the samples were extracted with 30ml of 15% KCI solution to measure ammonium nitrogen ($NH_4^+$-N) from the mineralization process. Results showed that Total nitrogen (TN) across all soil experiment in 12 week observations for the paste fertilizer and urea maintain very similar and there is no fertilizer type caused TN loss. Based on the $NH_4^+$–N accumulation was consistently higher under urea than paste fertilizer, reflecting the faster hydrolysis and stronger temperature responsiveness of urea-derived nitrogen. In both Inceptisols, $NH_4^+$ accumulation increased with temperature, with the 30 °C treatments exhibiting the most rapid and pronounced mineralization, followed by moderate release at 20 °C and 10 °C. The Andosol soil showed the lowest overall ammonium levels due to its higher adsorption capacity. These characteristics suggested that potential advantages of paste fertilizer for minimizing early-season nitrogen losses in flooded paddy soils and improving nitrogen-use efficiency under variable temperature conditions.

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# Fairy Ring Presence Alters Fungal-Soil Carbon/Nitrogen Dynamics and Stable Isotope Ratios

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**ABSTRACT**

Fairy ring fungi (FRF) are basidiomycete species that can form fairy rings characterized by a thriving concentric vegetation zone with high plant biomass. Nevertheless, how the presence of those FRF affects soil bioavailable C and N is poorly understood. Fungal and soil samples were collected from China, and their stable isotope characteristics were determined to elucidate the influence of fairy ring presence on carbon and nitrogen cycling in fungal-soil interactions. The results showed that there were substantial differences in $\delta^{13}C$ and $\delta^{15}N$ between fairy ring fungi and soil. The $\delta^{13}C$ values ranged from -22.12‰ to -16.44‰ in fungi and from -25.30‰ to -22.08‰ in soil. Similarly, the $\delta^{15}N$ values ranged from 4.91‰ to 12.75‰ in fungi and from 3.22‰ to 7.75‰ in soil. Notably, soil $\delta^{15}N$ was significantly higher inside the fairy ring than outside it. The presence of fairy ring fungi affected the carbon and nitrogen content of the surrounding soil and altered the abundance of stable isotopes, with different soil regions exhibiting distinct characteristics. Therefore, the presence of fairy rings plays a dominant role in fungal-soil interactions.

**Key words:**fairy ring; natural abundance of carbon and nitrogen isotopes; fungal-soil interaction; stable isotope ratio.

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# Exogenous input stoichiometry regulates the spatiotemporal synchronization of soil nitrogen supply and maize demand: A microbiome-driven mechanism

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## ABSTRACT

Optimizing the nitrogen (N) synchrony between soil supply and crop demand underpins resource-efficient agricultural production, whereas conventional one-time fertilization typically induces a temporal mismatch that compromises N use efficiency (NUE). Although substituting chemical fertilizers with pig slurry holds considerable potential for intensifying N-related productivity of crops, its low carbon (C) content and abundant ammonium ($NH_4^+$-N) concentration elevate the risk of soil mineral N (MN) accumulation and associated losses. Integrating C-rich straw with pig slurry regulates the C:N stoichiometric ratio of exogenous inputs, potentially mitigating MN accumulation and supply-demand asynchrony across the maize growing season. However, the underlying microbial mechanisms remain unclear. Therefore, we conducted a field split-plot experiment comparing two straw management practices—straw mulching (SM) and no straw (NS)—combined with three pig slurry substitution ratios (0%, 20%, and 40%) to investigate soil N dynamics and metagenomic functional shifts throughout vegetative (seedling, jointing) and reproductive (blister, maturity) growth phases. Key findings were as follows: (I) compared to sole slurry substitution (NS-20%, NS-40%), combining straw with slurry (SM-20%, SM-40%) functioned as a distinct "phasic regulator", more effectively synchronizing soil N supply with crop demand by maintaining lower MN levels during the seedling stage and enhancing soil N availability during the blister stage; (II) mechanistically, the phasic regulation was driven by a functional restructuring of the soil microorganisms, where SM-20% and SM-40% reduced MN accumulation during the seedling stage by prioritizing assimilatory retention (e.g., enriched genes of *nirA*, *nasA*, *gs_K00266*) over dissimilatory turnover (e.g., enriched genes of *narG*, *narJ*, *gdh_K00261*) relative to NS-20% and NS-40%, while subsequently shifting toward N acquisition during the blister stage via the enrichment of N fixation (e.g., *nifW*, *nifK*, *nifD*) and organic N degradation (e.g., *gdh_K15371*) genes; (III) exogenous C:N stoichiometry primarily regulated microbial functional shifts by stimulating microbial biomass, a process coupled with an improved physicochemical environment (e.g., pH and moisture) fostered by straw addition; (IV) multidimensional assessment identified SM-20% as the optimal strategy, achieving higher maize productivity (increased yield and economic benefits by 4.6% and 5.4%, respectively) and lower MN-related environmental risks compared to SM-40%. By synthesizing these findings, a "Stoichiometric Adaptation Cascade" framework was proposed, delineating how exogenous input stoichiometry modulates the transition in soil N cycling across the maize growing season. Accordingly, regulating exogenous C:N stoichiometry through rational organic combination establishes a viable paradigm for tightening soil N cycling and promoting sustainable agriculture in intensive maize cultivation.

**Keywords:** Phasic regulation; Metagenomic sequencing; Mineral nitrogen; Maize growing season; C:N ratio

**Acknowledgments**

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# Estimating fractions of $N_2O$ emissions from nitrification and denitrification using data assimilation

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## ABSTRACT

Nitrous oxide ($N_2O$) is a potent greenhouse gas contributing to global warming and stratospheric ozone depletion. $N_2O$ is primarily produced through nitrification and denitrification, which are regulated by soil and environmental factors. Numerous studies have been conducted to investigate nitrification and denitrification processes, their controlling factors and their contributions to $N_2O$ production. However, it is still challenging to estimate the parameters of process-based models based solely on limited experimental data. A fixed ratio is used in these models to estimate the proportion of $N_2O$ emissions from nitrification and denitrification. These unknowns may also result in uncertain predictions of feedback to N management practices and environmental conditions.

The application of nitrification inhibitors (NIs) e.g., 3-methylpyrazole 1,2,4-triazole (3MPTZ), 3,4-dimethylpyrazole phosphate (DMPP), acetylene ($C_2H_2$) is widely used to reduce $N_2O$ emissions. NIs could delay the oxidation of $NH_4^+$ to hydroxylamine, the first step of nitrification, thus decreasing the amount of $NO_3^-$, which is susceptible to leaching and loss through denitrification. While many process-based models simulate $N_2O$ emissions, their capacity to represent NIs' impact on N cycling is constrained by the lack of an NI module and relevant parameters.

Data assimilation improves model accuracy and reliability by calibrating models against observations, integrating mechanistic models with experimental data to estimate unmeasurable parameters and reduce associated uncertainties for better forecasts. In this study, we incorporated data assimilation into a coupled carbon–nitrogen model to estimate soil nitrification, denitrification, $N_2O$ emissions, and their related parameters under various soil moisture levels (Water-filled pore space (WFPS) at 50% and 70%), incubation temperature (15, 25 and 35°C) and nitrification inhibitor application (DMPP, 3MPTZ and $C_2H_2$) in cereal and vegetable production systems in Australia.

We found that the contribution of nitrification to $N_2O$ emissions (i.e., the fraction of $N_2O$ emitted from nitrification, $f_{N2O_nit}$) decreased with increasing temperature and moisture content, whereas denitrification dominated $N_2O$ production (i.e., the fraction of $N_2O$ emitted from denitrification, $f_{N2O_dni}$) under 70% WFPS regardless of temperatures. Under fertilizer N application, the use of nitrification inhibitors decreased $f_{N2O_nit}$) but increased $f_{N2O_dni}$). The efficacy of nitrification inhibitors in mitigating $N_2O$ emissions varied with environmental conditions. In this study, we demonstrate the use of data assimilation to constrain key parameters for predicting nitrification, denitrification and associated $N_2O$ emissions in response to soil environments and management practices. Integrating this technique into ecosystem process-based models has the potential to enhance model accuracy by reducing uncertainties and biases.

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# Organic fertilization reduces microbial nitrogen use efficiency by increasing resource availability and alleviating stoichiometric imbalances

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## ABSTRACT

Microbial nitrogen use efficiency (NUE), which governs the partitioning of N between microbial growth and mineralization, determines soil N supply and retention in croplands. However, the mechanisms driving the response of microbial NUE to fertilization at regional scales remain uncertain. Using a dual-isotope ($^{18}O$ and $^{15}N$) labeling approach across 12 long-term experimental sites in China, we found fertilization significantly decreased microbial NUE (log-response, RR = -0.48 ± 0.45, $P < 0.05$) compared to the unfertilized control, with organic amendments (manure and straw) exerting a greater reduction (median RR = -0.61) than chemical fertilizer alone (median RR = -0.35). This reduction was mediated by an enhancement in microbial N-acquiring enzyme activity, which increased soil total dissolved N. The magnitude of microbial NUE reduction was predominantly regulated by changes in soil properties (e.g., soil pH and total dissolved N) and microbial physiological traits (e.g., extracellular enzyme activity and stoichiometry), which together explained 83.5% of the response variance. Organic inputs enhanced this suppression by more effectively alleviating soil C:N imbalance and P limitation, as reflected in a greater decrease in microbial enzyme vector angle. Furthermore, climate (mean annual temperature) contributed 12.3% to the explained variance and was negatively correlated with microbial NUE response, indicating that warmer conditions amplified the fertilization-induced decline in microbial NUE. Overall, these mechanistic insights provide a theoretical basis for harnessing organic amendment strategies to regulate microbial function and improve soil N supply in croplands of China, with potential implications for soil N fate and developing region-specific fertilization regimes.

# Effects of manure substitution on nitrous oxide emissions in a subtropical Ultisol

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**ABSTRACT**

Manure substitution is widely promoted as a sustainable alternative to synthetic nitrogen (N) fertilization, yet its effects on nitrous oxide ($N_2O$) emissions remain highly variable, particularly in phosphorus (P)-limited subtropical soils. Here, we investigated how P availability mediates the response of $N_2O$ emissions to partial manure substitution by combining soils from a 21-year fertilization experiment with controlled laboratory incubations and $^{15}N$ tracing techniques. We compared two fertilization regimes: N-only and N plus P (NP), under which 30% of synthetic N was replaced by manure-N.

Manure substitution exerted contrasting effects on $N_2O$ emissions depending on P supply, increasing emissions under the N-only regime while reducing them under the NP regime. These divergent responses were closely linked to shifts in gross N transformation pathways. Under N-only conditions, manure substitution stimulated autotrophic nitrification and denitrification, enhancing $N_2O$ production. In contrast, under NP conditions, manure substitution reduced the contribution of heterotrophic nitrification to total $N_2O$ flux, despite unchanged process rates, coinciding with a significant enrichment of *nosZ* clade II genes.

Our findings demonstrate that the mitigation potential of manure substitution is strongly context dependent and critically regulated by P availability. By reshaping microbial N transformation pathways rather than uniformly suppressing $N_2O$ production, P supply determines both the direction and magnitude of $N_2O$ responses to organic fertilization in subtropical Ultisols.

**Acknowledgments**

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# Patterns and Mechanisms of Nitrogen Uptake, Utilisation and Loss in Different Rice Varieties

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**ABSTRACT**

With the continuous increase in nitrogen fertilizer application rates, environmental issues caused by nitrogen loss have become increasingly severe. In flooded paddy fields, ammonia ($NH_3$), nitrogen gas ($N_2$), and nitrous oxide ($N_2O$) emissions are recognized as the main pathways of nitrogen loss. Previous research has largely focused on optimizing nitrogen fertilizer management, while insufficient attention has been paid to the regulatory role of rice varieties themselves, the contributions of fertilizer and soil sources to gaseous nitrogen loss, and whether a trade-off exists between $NH_3$ and $N_2$ losses. This study investigated flooded rice in southern China, quantifying nitrogen uptake and emissions of $N_2$, $NH_3$, and $N_2O$ synchronously across different varieties throughout the entire growing season. Using $^{15}N$ isotope labeling techniques, the contributions of fertilizer and soil to $N_2$ and $NH_3$ losses were clarified, and the balance between their emissions was preliminarily explored. Pot experiments included three conventional varieties with significantly differing biomass levels, one nitrogen-efficient variety, and the nitrogen-efficient variety with a 20% nitrogen reduction treatment. Results showed that different varieties varied significantly in nitrogen uptake and utilization throughout the growing season, with higher-biomass varieties exhibiting greater nitrogen uptake capacity. Although total gaseous nitrogen loss showed no significant difference among the three conventional varieties, loss patterns varied across growth stages due to differences in nitrogen translocation capacity. Nitrogen-efficient genotypes reduced gaseous nitrogen ($NH_3$, $N_2$) loss by 13% and increased nitrogen retention in the soil. Under the 20% nitrogen reduction treatment, the nitrogen-efficient variety not only maintained stable yield but also increased nitrogen uptake by 10% while reducing soil nitrogen residue by 10%. The study further revealed significant varietal differences in the contributions to $N_2$ and $NH_3$ losses, with fertilizer and soil sources playing distinct roles depending on the variety. Nitrogen-efficient genotypes increased the fertilizer contribution to nitrogen loss, whereas the nitrogen reduction treatment lowered fertilizer-derived loss and raised the soil nitrogen contribution. A potential balance between $NH_3$ and $N_2$ losses was also preliminarily identified: $NH_3$ loss dominated during basal and tillering fertilization stages, while $N_2$ loss prevailed during panicle fertilization. This research highlights the potential of variety selection in reducing nitrogen loss and provides new insights for strategies that combine varietal improvement and optimized fertilization to minimize nitrogen loss.

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# Effect of Soil Moisture on Nitrous Oxide ($N_2O$) Emission from Two Intensively Cultivated Agricultural Soils in Sri Lanka – A Microcosm Study

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**ABSTRACT**

Nitrous oxide ($N_2O$) is a potent greenhouse gas that significantly contributes to global warming and climate change. Agricultural soils are among the main anthropogenic sources of $N_2O$, driven by nitrogen fertilization and soil moisture dynamics that influence microbial nitrification and denitrification. A microcosm study was conducted to estimate the $N_2O$ emission from intensively cultivated Alfisol and Ultisol collected from *Mahaillupallama* and *Nuwara Eliya*, Sri Lanka, respectively. Soil samples were incubated under two moisture levels, 60% and 90% water-filled pore space (WFPS), with three treatments: non-amended control, urea alone, and with a biological nitrification inhibitor added at 2% (v/w). Headspace gases were collected after 1, 5, 15, and 30 days and assessed for $N_2O$ concentration, while soils were assessed for ammonium ($NH_4^+$) and nitrate ($NO_3^-$) concentrations. Results revealed that urea application significantly increased ($p<0.05$) $N_2O$ emissions with peaks of 0.81 and 667.20 $N_2O$ µg/kg/h in Alfisol and Ultisol, respectively, at 90% moisture level until the 15$^{th}$ day. At 60% WFPS, a significant reduction ($p<0.05$) in $NH_4^+$ concentration and a simultaneous increase in $NO_3^-$ concentrations and $N_2O$ emission imply a significant contribution made via the nitrification pathway to the $N_2O$ emission in both soils. At the 90% WFPS, a simultaneous reduction in $NO_3^-$ concentrations and an increase in $N_2O$ emissions from both soils suggest a significant role played by denitrifiers in $N_2O$ emission. The biological inhibitor added to Alfisol led to an accumulation of $NH_4^+$ while reducing $NO_3^-$ concentration and $N_2O$ emission until the 15$^{th}$ day at both moisture levels. In contrast, inhibitory effects on nitrifiers were not evident in the Ultisol, and $N_2O$ emission increased partly due to an increase in the carbon substrate for denitrifiers. The maximum nitrification rate (Vmax) and the substrate saturation constant (Km) of Alfisol were 5.74 µg $NO_3^-$ N/kg/h and 0.84 µM, respectively, whereas in Ultisol, comparatively higher Vmax (46.94 µg $NO_3^-$ N/kg/h) and Km (1.03 µM) were reported. These results imply that the substrate affinity of nitrifying communities differed between the two soils, implying differences in the diversity of bacteria and archaea communities. The results emphasize the need of managing soil moisture content and substrate availability for biochemical pathways that produce $N_2O$, the possibility of using nitrification inhibitors to control $N_2O$ emission from the studied soils, taking microbial community characteristics into account.

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# Global distribution and genomic traits of soil nitrous oxide source-sink microorganisms

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## ABSTRACT

Nitrous oxide ($N_2O$) is a major long-lived greenhouse gas and an ozone-depleting substance. Soils are a key global source, and net $N_2O$ fluxes are governed by microbially mediated source-sink processes. The enzymatic steps most directly linked to $N_2O$ source and sink include the reduction of nitric oxide (NO) to $N_2O$ by nitric oxide reductase (NOR), followed by the reduction of $N_2O$ to dinitrogen ($N_2$) by nitrous oxide reductase (NosZ). Although research on NOR and NosZ diversity has expanded our view of potential microbial $N_2O$ sources and sinks, we still lack an integrated understanding of which taxa carry different NOR/NosZ types, how these taxa are distributed across habitats, and which genomic traits underpin their metabolic potential and environmental adaptation. These gaps limit the translation of microbial insights into actionable strategies for soil $N_2O$ mitigation.

Here, we integrate soil microbial genomes with environmental metadata at the global scale to identify NOR/NosZ-associated microorganisms and characterize their taxonomic diversity and ecological distributions. We then conduct comparative analyses of metabolic and adaptive signatures, evaluate their associations with environmental gradients, and identify functional modules and ecological strategies potentially underlying variation in soil $N_2O$ source-sink strength.

The results are expected to provide a foundation for screening and cultivating mitigation-oriented microorganisms. Guided by the identified taxa and genomic traits, candidates with high $N_2O$ mitigation potential and broad environmental tolerance will be prioritized, and targeted enrichment and isolation will be pursued. Together, these findings provide a theoretical basis for developing microbe-driven strategies to mitigate soil $N_2O$ emissions.

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# A mechanistic framework to explain variability in nitrification inhibitor performance across soils

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**ABSTRACT**

Nitrification inhibitors are widely used to reduce the loss of nitrogen fertiliser from soil and associated environmental impacts. Similar to urease inhibitors, proposals have been made to mandate their use in agricultural systems. However, the effectiveness of nitrification inhibitors remains highly variable, with inconsistent performance across soils and environmental conditions limiting confidence in their widespread adoption.

This presentation synthesises recent mechanistic insights and builds upon existing conceptual frameworks to examine how soil physical, chemical, and biological properties regulate nitrification inhibitor behaviour and efficacy. Key factors influencing performance are discussed, including soil pH, sorption processes, microbial activity, and environmental conditions that govern inhibitor persistence and bioavailability.

By integrating these mechanisms, this framework provides a structured basis for interpreting observed variability in nitrification inhibitor performance and highlights knowledge gaps requiring targeted investigation. The framework is intended to support more predictive use of nitrification inhibitors and to guide future experimental and modelling approaches aimed at improving nitrogen management across diverse soil systems.

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# Mechanistic insights into microbial pathways for nitrate loss in forest ecosystems

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## ABSTRACT

Nitrogen (N) cycling is fundamental to forest ecosystem functioning, with nitrate availability largely dictating N-loss from soils. Beyond leaching, microbial communities reduce nitrate via three competing dissimilatory pathways: denitrification (DNF; N loss to $N_2$ and $N_2O$), anaerobic ammonium oxidation (AMX; N loss to $N_2$), and dissimilatory nitrate reduction to ammonium (DNRA; N retention). Despite the ecological importance of these competing processes, their simultaneous quantification and the factors governing their partitioning remain poorly understood. Here, we integrated isotopic, modeling, and molecular approaches to assess nitrate partitioning along forest hillslope gradients. We found that the competition for nitrate was dominated by DNRA at the top of hillslopes (up to 74%), which decreased and in exchange for a higher contribution from DNF (up to 96%) when approaching the bottom of the hillslope. The magnitudes of DNRA and AMX rates (up to 3.6 and 5.8 μg N $g^{-1}$ $h^{-1}$, respectively) underscore their underestimated significance in forest N budgets. Notably, the N-limited forest partitioned more nitrate to DNRA (26.4%) compared to the N-rich forest (19.4%), indicating a microbial adaptation toward N conservation under nutrient scarcity. Moving forward, we will investigate the specific factors governing the competition among these three pathways, alongside the $N_2O$ and $N_2$ product stoichiometry of DNF. This will inform the development of N management strategies aimed at enhancing N-use efficiency and climate mitigation in forest and managed ecosystems.

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# Long-term atmospheric nitrogen deposition and environmental impacts in a subtropical watershed in Central China

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**ABSTRACT**

Atmospheric nitrogen (N) deposition is an important N source for ecosystems in China in recent years, driven by reactive N emissions from agricultural and industrial production as well as transportation. The long-term variation of atmospheric N deposition at the watershed scale and its environmental impacts remain insufficiently explored in regions with high N deposition, such as Central China. This study investigates the spatio-temporal variation of atmospheric N deposition in an agricultural watershed in subtropical Central China from 2011 to 2025. Atmospheric wet and dry N deposition were measured at typical paddy field, tea field, and forest sites. We assessed the impacts of atmospheric N deposition on soil $N_2O$ emissions and riverine N export using $^{15}N$ isotopic tracing. The results showed that atmospheric N deposition ranged from 25.7 to 41.5 kg N $ha^{-1}$ $yr^{-1}$ across the ecosystems over the 15-year period. Dry N deposition showed a significant decreasing trend across all sites, while wet deposition showed no significant change. The reduced N fraction in total deposition exceeded 0.5 in all three land-use types. Notably, the ratio of reduced to oxidized N in paddy fields showed an increasing trend, indicating that agricultural emissions remain the primary source of regional deposition. The contribution of N deposition to $N_2O$ emissions was 0.14% in paddies and 0.72% in tea fields, slightly lower than the IPCC emission factors for fertilizer (0.3% and 1%, respectively). Natural $^{15}N$ tracing also showed that atmospheric N deposition contributed over 20% to riverine N in the watershed. This study demonstrates that atmospheric N deposition significantly affects soil $N_2O$ emissions and non-point source water pollution in subtropical Central China.

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# Soil rather than fertilizer dominates N2 emissions in flooded paddy fields

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## ABSTRACT

Rice production underpins food security but relies heavily on nitrogen (N) fertilization, of which is lost from flooded paddies as gaseous emissions. Dinitrogen ($N_2$) represents the largest N loss, yet its sources remain poorly constrained because biological $N_2$ fluxes are difficult to quantify against the atmospheric background. Global N budgets and mitigation strategies typically attribute $N_2$ emissions mainly to fertilizer, largely overlooking soil N pools. Here we apply a novel in-situ $^{15}N$ tracing–membrane inlet mass spectrometry ($^{15}N$-MIMS) technique to simultaneously measure $N_2$, $NH_3$ and $N_2O$ emissions and partition their soil- versus fertilizer-derived origins across a full growing season in two rice cultivars. We find that soil organic nitrogen (SON) accounts for most $N_2$ emissions (72-75%), overturning the prevailing assumption that fertilizer dominates this loss pathway, which is independently confirmed by a 13-year long-term fertilization experiment. In contrast, $NH_3$ originates mainly from fertilizer (71-77%) and $N_2O$ derives from both sources in near-equal proportions. We identify a previously unrecognized microbial N pump in which rapid assimilation of fertilizer-derived $NH_4^+$ accelerates SON mineralization, fueling soil-sourced $N_2$ emissions and driving a seasonal shift from $NH_3$- to $N_2$-dominated N losses. Neglect SON contributions causes systematic overestimation of fertilizer-derived $N_2$ and $NH_3$ losses by ~26%. These findings fundamentally revise N budgets for flooded rice systems and demonstrate that fertilizer reduction alone is insufficient to curb N loss, highlighting the need to manage soil-microbe-plant interactions to sustain yields while minimizing environmental impacts.

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# Nitrogen Characteristics and Sustainable Management in Global Sloping Croplands

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**ABSTRACT**

Sloping croplands are vital for global food security yet represent a vulnerable nexus of soil erosion and nutrient loss. While the impacts of topography on local productivity are well-documented, a systematic global assessment of how slope gradients drive nitrogen (N) budgets and nitrogen use efficiency (NUE) remains a critical knowledge gap. This limitation hinders the development of spatially targeted policies for sustainable agricultural management.

To address this, we developed a global analytical framework integrating high-resolution land use data, topography, and N cycling processes. We mapped the spatiotemporal patterns of global sloping croplands and quantified N inputs, outputs, and NUE across slope classes using the Coupled Human and Natural Systems (CHANS) model. Furthermore, we designed optimization scenarios aligned with Sustainable Development Goals (SDGs), evaluating the potential of cropland reallocation (retiring steep-slope farming) and crop mix optimization to enhance productivity and NUE.

Our results reveal distinct topographic controls on the global N cycle: (1) Gradient Effect: Both N inputs and outputs decrease significantly with increasing slope. Crucially, N outputs decline faster than inputs, leading to a structural decline in NUE on steeper terrains. (2) Regional Disparity: Asia dominates global N output on sloping lands, whereas Africa and Oceania exhibit significantly lower intensities, highlighting diverse management challenges. (3) Optimization Potential: Scenario simulations demonstrate that reallocating cropland from steep to flatter terrains globally can substantially improve NUE and mitigate environmental N losses. However, regional-scale crop structure adjustments offer a more cost-effective and feasible pathway. This study uncovers the structural influence of slope on global N cycling and provides actionable scientific support for achieving sustainable agricultural transitions.

**Keywords:** Sloping cropland; Nitrogen cycling; CHANS model; Sustainable Development Goals (SDGs)

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# Optimizing the C: N Ratio of N-Enriched Biochar Enhances Soil Nitrogen Dynamics, Enzyme Activity, and Crop Productivity under Reduced Nitrogen Inputs

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**ABSTRACT**

The application of biochar to improve soil fertility and productivity is a well-established practice; however, the impact of its C:N ratio and interaction with nitrogen (N) application rates on crop performance remains poorly understood. This study investigates N-enriched biochar (NB) with varying C:N ratios on N fractions, as well as maize and wheat growth and yield, providing novel insights into the relationships between biochar, N dynamics, and crop productivity. A pot experiment evaluated the effects of biochar type and N application rate on soil properties and crop performance. The treatments consisted of three biochar types [pristine biochar (PB), and two NB types (NB1 and NB2)], and non-biochar control (CK)combined with three N fertilizer rates: 100% (N100), 70% (N70), and 40% (N40) of the recommended dose. The results demonstrated that the NB1 and NB2 significantly enhanced soil N availability, indicated by increased $NO_3^-$-N and available N (AN) concentrations, alongside improved N use efficiency traits, regardless of the N application rate. Notably, the NB1 at N70 increased soil organic matter (SOM)by 20.5% in maize and 18.5% in wheat at maturity, respectively. Furthermore, NB1 at N70 also significantly elevated key enzymes activities N-acetyl-glucosaminidase (NAG) and leucine aminopeptidase (LAP) by 64.3% to 114.9% across growth stages and crops. The improved soil N dynamics and enzymatic activities directly enhanced crop growth and productivity. NB1 at N70 achieved the highest grain yield and harvest index (HI), with maize yields increasing by 44.5% and 42.9%, and wheat by 69.5% and 49.5%, respectively. Additionally, NB application improved photosynthetic efficiency and chlorophyll content, even under reduced N rates. These findings suggested that the applying NB1 at 70% of the recommended N rate can significantly improve soil N dynamics, enzymatic activities, and photosynthetic efficiency, ultimately promoting crop growth and yield.

**Keywords:** Biochar; C:N ratio; Enzymes; Nutrient use efficiency; photosynthetic efficiency; Soil organic matter.

**Acknowledgments**

The study was supported by the Agricultural Key-scientific and Core-technological Project of Shaanxi Province (2025NYGG011), the Agricultural-Photovoltaic Complementary Project of China Datang Dali New Energy Co., Ltd. (DTDL-XNY-2023-025), and the National Natural Science Foundation of China (41877541).

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# Nitrogen cycling in the soil-plant continuum in multispecies swards: insights from a miniature sward experiment

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**ABSTRACT**

Temperate grazing systems are shifting from perennial ryegrass (*Lolium perenne*; PRG) monocultures to multispecies swards to address limitations of poor persistence of PRG under drought and heat conditions. They are seen as unsustainable because of high seed costs and the need for nitrogen (N) fertilizers for yield. Similarly, in binary systems with grass and legumes, even though clover contributes additional N through biological nitrogen fixation (BNF), it often leads to a decline in clover persistence and overall sward diversity in high input systems. Research has shown that the multispecies plant's diverse functional traits may affect plant-soil nutrient utilization and water uptake. However, there is still much to learn about their role in influencing N use efficiency (NUE) and soil health within multispecies use in dairy farming. To address this, we conducted a yearlong macrocosm experiment using 6 common forage species consisting of grasses (PRG and cocksfoot); forbs (plantain and chicory) and legumes (white clover and red clover) grown in various combinations. The species effect and interactions were studied by investigating belowground N turnover in a legume-forb-grass system using a $^{15}N$ leaf labelling method. A single leaf of white clover was labelled with 98% enriched $^{15}N$ urea to trace the movement of N to its companions, PRG, cocksfoot, plantain and chicory and into the soil. Comparisons were made between individual plant pairing (i.e. clover-grass) and complex mixtures (i.e. clover-grass-plantain-chicory). We tested the hypothesis that multispecies swards improve N cycling efficiency compared to traditional PRG based systems based on their functional traits.

The finding will reveal ways to address challenges to manage more environmentally sustainable pastures while reducing reliance on N fertilizers and simultaneously improving herbage production, soil health, and pasture sustainability in the Australian dairy farming industry.

**Acknowledgments**

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# Quantify gaseous nitrogen production from agricultural soils using a microbial-explicit model

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**ABSTRACT**

Agricultural soils are a major source of anthropogenic nitrous oxide ($N_2O$), but their $N_2O$ emission estimates are highly uncertain, mainly due to the complexity of nitrogen (N) processes. Most soil N models include only primary N processes such as nitrification and denitrification, which limits their ability to realistically simulate N transformations in soils and accurately estimate $N_2O$ emissions from soils. This study introduces a Microbial-Explicit Model incorporating Comprehensive Nitrogen processes (MEMCN) to evaluate and quantify the influences of various N processes on the production of $N_2O$ as well as NO and $N_2$, including nitrification, denitrification, anaerobic ammonium oxidation (ANAMMOX), dissimilatory nitrate reduction to ammonium (DNRA), mineralization, and microbial assimilation (i.e., growth) and death. The MEMCN was evaluated in laboratory experiments using agricultural soils with different levels of N additions under anaerobic and aerobic conditions, and reproduced well the dynamics of $NH_4^+$, $NO_3^-$, $NO_2^-$, NO, $N_2O$, and $N_2$. After nitrification and denitrification, ANAMMOX and assimilation were found to be most important in controlling N transformations in agricultural soils. ANAMMOX directly increased $N_2$ emissions by 139% at the beginning of the simulations (i.e., 48 h) under anaerobic conditions, while microbial assimilation indirectly reduced NO, $N_2O$, and $N_2$ emissions by 88%, 54%, and 58%, respectively, at the end of the simulations (i.e., 336 h) under aerobic conditions. Correspondingly, the biomass of ANAMMOX bacteria increased significantly at the beginning of the simulations under anaerobic conditions, while the biomass of nitrite oxidizing bacteria increased substantially under aerobic conditions. In contrast, DNRA, mineralization and microbial death had minor effect on soil N transformations, and the biomass of DNRA bacteria and heterotrophs did not change significantly during the simulations. Our study shows that it is necessary to include ANAMMOX and microbial assimilation in soil N models, while explicit simulation of microbial biomass dynamics may only be necessary if microbial biomass pools change significantly.

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# Dynamic Hydrological Connectivity Regulates the Transport and Transformation of Soil Derived $N_2O$ in a Subtropical Karst Critical Zone

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## ABSTRACT

Subtropical forests in South China receive high atmospheric nitrogen inputs. These inputs stimulate strong nitrous oxide ($N_2O$) production in soils and in the underlying critical zone. In karst landscapes, highly permeable subsurface pathways rapidly transfer soil nitrogen into shallow aquifers. Karst springs are now recognized as hotspots of indirect $N_2O$ emissions, while the processes that control the transport, transformation and release of soil derived $N_2O$ remain unclear. Hydrological connectivity between hillslope soils, the epikarst and springs is often ignored.

We investigated this problem along a hydrological transect at the Yaji Karst Experimental Site in Guilin, China. The transect connects forest soils, the epikarst zone and a perennial spring. Event based sampling captured conditions from dry baseflow to intense rainfall. We measured soil $N_2O$ fluxes, dissolved gases and inorganic nitrogen species, stable isotopes and microbial functional genes along the flow path. These observations describe the saturation state and isotopic evolution of $N_2O$ from soils to the spring outlet. We use this integrated dataset to reveal how hydrological regimes control soil derived $N_2O$ from production to emission. Storm driven hydrological connectivity can flush $N_2O$ that has accumulated in hillslope soils and shallow groundwater. The same events also change subsurface oxygen and substrate conditions and thus alter in situ $N_2O$ production and reduction.

The study links soil nitrogen transformations in the critical zone with indirect $N_2O$ emissions from karst springs. The results will enable refined $N_2O$ assessment in subtropical karst landscapes by linking production, transport and release, while characterizing divergent responses to different events.

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# An open-path nitrous oxide laser analyzer for eddy covariance flux

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**ABSTRACT**

As a significant greenhouse gas (GHG), nitrous oxide ($N_2O$) is primarily emitted through anthropogenic activities, with agriculture being the predominant source. These emissions often occur across large spatial scales. Beyond the effects of global warming, $N_2O$ is part of the reactive nitrogen (Nr) cycle, contributing to environmental problems such as water pollution, soil acidification, and biodiversity loss.

Monitoring $N_2O$ remains technically challenging due to its low atmospheric background (~330 ppb) and short-term, high-intensity emissions triggered by rainfall or fertilization. These spatiotemporal variabilities demand high-frequency, sensitive detection methods.

This work introduces an open-path $N_2O$ laser analyzer (Model: HT8500, HealthyPhoton Co., Ltd.) designed for future applications in $N_2O$ monitoring and EC flux measurements. The HT8500 utilizes an quantum cascade laser (QCL) to probe the mid-infrared transition of $N_2O$ at 4.54 μm. The specific absorption peak has the advantage that the density and spectroscopic effects compensate for each other, resulting in low temperature-related corrections in EC flux measurements. Laboratory experiments revealed that the HT8500 has a noise level of 0.3 ppbv at a 10-Hz sampling rate with a typical power consumption < 25 Watts.

A long-term field experiment based on the HT8500 over a bare agricultural field in Shandong, China was conducted to test “zero-flux” measurements and computations under different meteorological conditions. The field experiment demonstrated a detection limit of approximately 26.549 ug N $m^{-2} \cdot h^{-1}$, indicating that the low flux detection limit of HT8500 is similar to the commercial available chamber-based $N_2O$ flux measurement scenarios.

In the experiments conducted in Northeast China, the fertilization period was concluded, and the crops were basically mature. As temperatures decrease, the diurnal variation in $N_2O$ fluxes dropped significantly, indicating the influence of temperature on eddies when emission sources remain stable.

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# Reducing N-related environmental risk while achieving food security in China

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**ABSTRACT**

The widespread application of synthetic nitrogen (N) fertilizers, pivotal for boosting global food production, has come at a significant environmental cost. This is particularly true in China, where intensive agriculture has led to substantial emissions of reactive nitrogen (Nr), causing severe air and water pollution. Achieving food security while minimizing environmental risks remains a critical challenge. This study aims to quantify the historical trajectory of N flows in China and identify a sustainable pathway that reconciles these dual objectives. We constructed a long-term national N budget for the period 1961–2018 to analyze changes in N inputs, crop uptake, and environmental losses. Our findings reveal a growing disparity between actual N inputs and the levels required for both food production and environmental safety. The N inputs (including N fertilizer, manure, deposition and biological N fixation) necessary to meet China's food demand were 14, 21, 27, and 29 Tg N $yr^{-1}$ in 1961, 1980, 2000, and 2018, respectively. However, actual inputs surged to 4, 25, 39, and 48 Tg N $yr^{-1}$ for the same years, indicating significant over-application since 1980. Furthermore, since 2000, the actual inputs have consistently exceeded the critical environmental thresholds—35 Tg N $yr^{-1}$ to control ammonia emissions and protect air quality and biodiversity, and 28 Tg N $yr^{-1}$ to mitigate nitrate leaching and safeguard groundwater—thereby escalating environmental and health risks. We demonstrate that reducing N input from the current 48 Tg N $yr^{-1}$ to approximately 31 Tg N $yr^{-1}$ is achievable without compromising food security. This reduction can be realized through integrated strategies, including enhanced manure recycling, balanced fertilization, and improved soil-crop system management, which align with the principles of integrated nutrient management (INM). Such a transition would yield direct and indirect benefits estimated at EUR€30.4 (28.5–35.8) billion, substantially improving air and water quality, protecting ecosystems and human health, and advancing agricultural sustainability. This analysis provides a feasible 'win-win' roadmap for China's agricultural policy, emphasizing that the targets for required and critical N inputs are dynamic and can be optimized further through continued innovation in N management.

**Key words**: Historic N budget; Critical N inputs; Required N inputs; Soil-crop system management

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# Cultivating Resilient Crops: Nitrogen Management for Climate and SDG Benefits

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**ABSTRACT**

Nitrogen (N) is a crucial element for supporting life on Earth. It is involved in a vital biological process, namely nitrogen fixation. While nitrogen plays a significant role in food production and is essential for sustaining ecosystems, it also contributes to climate change by releasing reactive N. Nitrogen indirectly impacts climate change through the release of combined forms of N notably nitrous oxide, and its effects on ecosystems. Therefore, it is imperative to manage N emissions and adopt sustainable practices to mitigate climate change and achieve global climate goals.

Increasing N-use efficiency in agriculture has significant potential to mitigate climate change and contribute to resilient crop production. The quest for appropriate N-management needs accounting for the N-surplus in a production system and evolving strategies for increasing nitrogen use efficiency. Much effort has been made to this effect with varying success. Cutting-edge technological options are although available on the horizon, the success lies in improved awareness among the policymakers, stakeholders, and farmers, and better research to quantify the linkage between N-management and the SDGs, collectively.

This presentation will analyze the (1) different sources of N inputs and outputs in global cereal production, (2) global trends of synthetic fertilizer N recovery efficiency and losses, (3) effect of long-term addition of synthetic N on soil N storage, and (4) proposes various strategies available to improve the use efficiency of N in different regions.

**Keywords:** Nitrogen, Sustainable Development Goals, Cereals

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# Dynamic safe nitrogen boundary for maintaining surface water quality in China

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**ABSTRACT**

Nitrogen plays a critical role in Earth's biogeochemical cycles, acting both as an essential nutrient for life and an environmental pollutant. Managing nitrogen use within safe boundaries is crucial for achieving the Sustainable Development Goals, particularly under the pressures of a growing global population. Here we quantified the temporal dynamics in safe boundary for nitrogen input to the human-nature system in view of surface water quality in China, driven by changes in management practices and runoff over the period of 1980 to 2020. Insufficient nitrogen management in the human-nature system led to a reduction in the safe nitrogen boundary from 27 Tg N $yr^{-1}$ in 1980 to 17 Tg N $yr^{-1}$ in 2006. Subsequently, improvements in agricultural nitrogen use efficiency and urban waste management contributed to an expansion of this boundary, which reached 34 Tg N $yr^{-1}$ by 2020. Further integration of nitrogen management strategies spanning agriculture, urban waste, and human dietary patterns is needed to maintain nitrogen use within the established safe boundary by 2050, generating societal benefits of US$335 billion for ecosystems, human health, climate, and food supply, with associated implementation costs of US$106 billion. These findings demonstrate that improved nitrogen management practices can dynamically expand the safe operating space for higher nitrogen utilization to support human well-being while keeping nitrogen pollution within safe environmental limits.

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# Cutting global nitrogen emissions by one-third for balanced and achievable SDGs by 2030

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**ABSTRACT**

Achieving the Sustainable Development Goals (SDGs) by 2030 is becoming difficult as global progress lags. Nitrogen is key to food security and environmental sustainability, making its management crucial for advancing multiple goals within the timeline. Here, we introduce an SDG-driven framework to evaluate nitrogen management under sustainable shared socioeconomic pathways. We show that meeting balanced and achievable targets, defined as an average nitrogen-related SDG index score above 75 with individual target scores exceeding 60, requires reducing global nitrogen emissions by 50 million tonnes (Tg) by 2030, 32% of 2020 levels, entailing decreases of 30 Tg in the atmosphere and 20 Tg in aquatic ecosystems. Existing technological strategies can deliver only half of the required mitigation, even with investments of $176 billion that yield economic benefits of $291 billion. This highlights that technologies alone are insufficient, and meaningful progress toward the SDGs depends on integrating mitigation techniques with broader socioeconomic transitions.

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# Identifying active nitrate-assimilating bacteria that alleviate secondary salinization in facility soils

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## ABSTRACT

The elimination of nitrate constitutes a fundamental prerequisite for the remediation of secondary salinization in protected agricultural soils. Microbial assimilation-driven nitrate immobilization serves as an efficient pathway for removing excess soil nitrate, a process modulated by carbon-based amendments. Nevertheless, the key microbial taxa responsible for active nitrate assimilation and their specific responses to diverse carbon source additions remain inadequately characterized. To address this knowledge gap, a $^{15}N$-labeled nitrate tracing experiment was conducted on secondary salinized soil supplemented with eight distinct carbon sources (no-carbon control, glucose, xylan, cellulose, wheat straw, corncob, wood flour, and cow dung). The results demonstrated that glucose and xylan amendments induced the most rapid and substantial elevation in the gross nitrate immobilization rate—exhibiting 162.29- and 175.29-fold increases relative to the control within 7 days. This was followed by cellulose (26.84-fold) and corncob (18.68-fold) amendments. Parallel trends were observed in nitrate depletion dynamics, with significantly reduced residual $NO_3^-$-N concentrations detected in soils amended with glucose or xylan. Concomitantly, these two carbon sources also led to heightened nitrate loss and nitrous oxide ($N_2O$) emissions. Stable isotope probing targeting $^{15}N$-labeled DNA uncovered distinct nitrate-assimilating microbial communities associated with high-immobilization carbon sources. Specifically, unclassified Halomonas and Photobacterium taxa dominated the microbial assemblages in glucose- and xylan-amended soils, while unclassified Cellvibrio and Streptomyces emerged as the predominant groups in cellulose- and corncob-amended soils, respectively. Path analysis revealed that the primary determinant influencing nitrate immobilization rates was the community-level ribosomal RNA operon copy number of nitrate-assimilating bacteria. This factor exerted a more pronounced effect than other ecological attributes, including microbial diversity indices, community composition, and the abundance of nitrate assimilation-related genes. Indices reflecting carbon source availability—such as initial dissolved organic carbon content and microbial carbon source utilization (assessed via $CO_2$ efflux)—indirectly enhanced nitrate immobilization rates by promoting ribosomal RNA operon copy number and the abundance of assimilation genes. Collectively, this study identifies key nitrate-assimilating bacterial taxa and highlights the community-level rrn copy number as a critical functional trait governing microbial nitrate immobilization processes in secondary salinized soils.

# Effects of film mulching and straw retention on soil labile nitrogen pool, enzymes and ammonia volatilization in the root zone of winter wheat

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**ABSTRACT**

Film mulching and straw returning are common conservation tillage measures in arid regions. A long-term experiment was conducted to investigate the effects soil labile nitrogen pools and soil enzyme activities have on ammonia volatilization in the root zone of winter wheat under film mulching and straw retention. The experiment was arranged in Cao Xinzhuang experimental Farm of Northwest A&F University in 2017. A split-zone experimental design was used in this experiment. The main zones were conventional cultivation, straw return, and film mulching, while the secondary zones were no nitrogen application, conventional nitrogen application, and 20% reduction of conventional nitrogen application . 0~20 cm of wheat root zone soil was collected 42, 166, 194, and 217 days after sowing of winter wheat in the fifth season and inter-root soil of wheat was collected 42 days after sowing to determine soil nitrate-ammonium nitrogen, microbial biomass nitrogen, soil nitrate reductase, hydroxylamine reductase, and urease activities. The ammonia volatilization from agricultural soils was also collected during the wheat season in order to analyze the response of ammonia volatilization to the cultivation pattern, soil labile N pools, and soil enzymes. The results found nitrogen application significantly increased the content of soil unstable nitrogen pool, soil enzyme activity and ammonia volatilization. Total season ammonia volatilization accumulation in wheat to be significantly lower ($P$<0.05) in the film mulching treatments (6.41~7.38 kg·hm$^{-2}$) than in the straw return (8.37~9.45 kg·hm$^{-2}$) and conventional tillage treatments (8.81~11.06 kg·hm$^{-2}$) with identical fertilization levels. The microbial biomass N content was found to be significantly higher ($P$<0.05) in the straw return treatment compared to the conventional tillage and film mulching treatments. Soil ammonia volatilization was found to have a significant positive correlation with soil ammonium nitrogen, microbial biomass nitrogen, and urease activity under straw return treatment ($P$<0.05). It also had a significant positive correlation with soil ammonium nitrogen, microbial biomass nitrogen, hydroxylamine reductase, and urease activity under mulch treatment ($P$<0.01). Under 20% nitrogen reduction treatment, film mulching and straw returning can reduce ammonia volatilization, increase soil unstable nitrogen pool content and soil enzyme activity. This study can provide theoretical support for subsequently reducing ammonia volatilization losses and improving the utilization of N fertilizer.

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# Oxygen isotope anomaly identifies selective nitrate leaching from forest soils

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## ABSTRACT

Nitrate ($NO_3^-$) leaching is one of the major pathways of nitrogen loss from forest ecosystems and can degrade downstream water quality under elevated atmospheric nitrogen deposition. Soil $NO_3^-$ reflects a mixture derived from atmospheric $NO_3^-$ deposition and biologically nitrification, yet mechanisms governing which fractions of $NO_3^-$ are preferentially leached from forest soils remain unresolved. Conventional interpretations treat soil $NO_3^-$ as a homogeneously mixed pool and therefore assume that leached $NO_3^-$ inherits the source composition of bulk soils. This assumption is difficult to reconcile with hydrological evidence that preferential flow bypasses biogeochemically active microsites, decoupling transport from processing and potentially exporting a hydrologically accessible fraction of soil $NO_3^-$. Here, we develop a framework to quantify selective $NO_3^-$ leaching from forest soils using oxygen isotope anomaly ($\Delta^{17}O$), and partition soil $NO_3^-$ into two hydrologically distinct components: i) recycled $NO_3^-$ (r-$NO_3^-$) that has undergone microbial turnover and is retained in processing microsites, and ii) mobile $NO_3^-$ (m-$NO_3^-$) that is preferentially connected to rapid flow paths. Within this framework, $\Delta^{17}O$ not only enables direct source apportionment of $NO_3^-$ in both soils and streams but also acts as an integrative indicator of hydrological accessibility to leached $NO_3^-$. Using a global compilation of published $\Delta^{17}O$ data together with a forest investigation in a region under high atmospheric nitrogen deposition, we quantified the proportional contributions of m-$NO_3^-$ and r-$NO_3^-$ to stream exported $NO_3^-$, providing a leaching selectivity metric among forests. We further examined how leaching selectivity varies with key environmental controls, including atmospheric N deposition, precipitation regime, and soil properties. This work can help identify the conditions under which forests are more prone to $NO_3^-$ losses and increased downstream nitrogen pollution, and they support a more robust interpretation of environmental controls on nitrogen export.

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# Contrasting effects of drought periods on grassland nitrous oxide emissions are attenuated by nitrogen deposition

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## ABSTRACT

Atmospheric nitrous oxide ($N_2O$) concentrations have increased since the pre-industrial period. Climate change is driving more frequent and intense droughts across multiple seasons in dryland ecosystems worldwide, and anthropogenic activities has been elevating nitrogen (N) deposition. Grasslands potentially contribute 25% of natural soil $N_2O$ emissions globally. While the individual effects of drought and N deposition on grassland $N_2O$ emissions are relatively well-studied, the interactive effects of N deposition and drought period on $N_2O$ emissions remain poorly understood. Here, we conducted a two-year factorial experiment to elucidate whether and how N deposition modifies the effects of drought period on grassland $N_2O$ emissions. Drought treatments were imposed in early (E-Drought), late (L-Drought), and continuous (EL-Drought) throughout the growing season, each with and without N deposition, over two growing seasons. We found that drought impacts on soil $N_2O$ emissions in semi-arid grasslands strongly depended on the period of drought and N scenario. Without N deposition, E-Drought and EL-Drought increased emissions by 26% and 13% (effect sizes: +0.23 and +0.15), respectively. These effects were amplified by re-drought in the following year (effect sizes: +0.44 and +0.94). This is primarily due to reduced plant competition for soil NH4+, leading to higher NH4+ availability for ammonia-oxidizing archaea (AOA), subsequently promoting nitrification and $N_2O$ production. With N deposition, E-Drought and EL-Drought also increased $N_2O$, but with smaller effect sizes (+0.08 and +0.09). This dampened responses are mainly because the N deposition alleviated plant drought stress by improving plant physiological conditions, which enhanced plant N uptake and thereby reduced N availability for AOA in this N limited grassland. L-Drought reduced $N_2O$, with effect sizes increasing from -0.06 for the first drought to -0.34 for re-drought. Similar trends for L-Drought were also found under N scenario (Fig. 1). Our findings suggest that drought increases $N_2O$ emissions when occurring before peak plant biomass period. However, under elevated N deposition scenario in the future, drought effects would be masked. Thus, the impact of drought on $N_2O$ emissions in this grassland ecosystem may be less severe than predicted under scenarios of increasing N deposition, highlighting the importance of considering climate changes.



Fig.1 The conceptual framework of drought period effects on $N_2O$ emissions under N0 and N5 scenarios。

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# Free-living nitrogen fixation in paddy soils: integrating continental-scale drivers with phonologic dependent dissolved organic matter coupling

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**ABSTRACT**

Free-living biological nitrogen ($N_2$) fixation is increasingly recognized as an important, yet poorly constrained, N input in flooded rice paddy soils. Here we synthesize results from a continental-scale survey across China and a mechanistic field experiment to elucidate the magnitude, controls, and molecular mechanisms sustaining free-living $N_2$ fixation in paddy ecosystems. Using $^{15}N_2$ isotope tracing, metagenomics, metatranscriptomics, and ultrahigh-resolution FT-ICR MS, we link large-scale environmental gradients with phenological dependent dissolved organic matter (DOM) transformations and methane ($CH_4$) cycling.

Our results showed across 50 paddy soils spanning 4000 km in China, potential free-living $N_2$ fixation rates averaged 24 nmol N $g^{-1}$ $h^{-1}$ and were approximately an order of magnitude higher than dissimilatory nitrate reduction to ammonium, comparable to or exceeding combined $N_2$ losses from denitrification and anammox. Longitude and soil organic carbon were the dominant abiotic predictors of fixation rates, whereas ammonium exerted no detectable inhibition. Metagenomic analyses revealed that heterotrophic diazotrophs commonly co-encoded genes for organic carbon oxidation and nitrate respiration, supporting an energy-coupled mechanism sustaining $N_2$ fixation under anaerobic conditions.

Field experiments further demonstrated strong phenological regulation of $N_2$ fixation, with rates peaking at the seedling stage and declining toward harvest. Transcriptional regulation, particularly *nifA* expression, rather than gene abundance, best explained temporal variability in $N_2$ fixation. FT-ICR MS revealed that $N_2$ fixation and *nifA* transcription were positively associated with specific DOM traits, especially tannin-like and carbohydrate-like compounds, higher O/C ratios, and elevated nominal oxidation state of carbon. Phenological dependent DOM transformations, including demethylation and decarboxylation of tannin-like molecules, appeared to create transient thermodynamically favorable niches for diazotrophs. Notably, $N_2$ fixation was tightly coupled with methane cycling. Methane emissions and methanotroph gene expression (*pmoA/B/C*) covaried with $N_2$ fixation, and $CH_4$ addition stimulated fixation in straw-amended soils. DOM compounds correlated simultaneously with $CH_4$ metabolism and diazotrophic activity, indicating indirect support of $N_2$ fixation via DOM-driven methanogenesis and methanotrophy.

In summary, these results identify paddy soils as hotspots of free-living $N_2$ fixation sustained by interactive controls of organic carbon availability, DOM chemodiversity, microbial transcriptional regulation, and methane metabolism. This integrated C–N–$CH_4$ framework advances mechanistic understanding of N retention in rice systems and highlights management opportunities to enhance biological N inputs while maintaining soil fertility.

**Keywords:** Free-living $N_2$ fixation; Diazotrophs; DOM; High-resolution mass spectrometry; N retention

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# The potential of optimized agricultural management to reduce global cropland nitrogen losses within safe boundaries

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**ABSTRACT**

Although nitrogen (N) is an essential nutrient for plant growth and agricultural productivity, increased N inputs lead to elevated N losses, resulting in detrimental environmental consequences. This mainly includes the emission of nitrous oxide ($N_2O$) and ammonia ($NH_3$) to the atmosphere and the leaching and runoff of nitrate (NO3-) into water bodies. These N losses give rise to a range of significant environmental issues, including climate warming, increased concentration of fine particulate matter (PM2.5) in the air, ozone depletion, water eutrophication, soil acidification and biodiversity losses[1]. Addressing these issues is crucial for mitigating climate change and promoting environmental sustainability. Inversely, To reconcile required N inputs for food production of an increasing population (also denoted as the just N and boundaries) with acceptable N losses to protect the environment, also denoted as safe N boundaries, it is crucial to enhance the nitrogen use efficiency (NUE) and thereby reduce N losses.

In this key note lecture, I first give an overview of the variation in safe N boundaries as compared to current N inputs and of the required NUE increase to reconcile food production (just N boundaries) with environmental protection (safe N boundaries) at global scale[2] and continental scale[3, 4]. I then discuss the potential to attain such an NUE increase by the adoption of sustainable nutrient, crop and soil management practices in agriculture systems[5] and thereby reduce N losses[6]. Nutrient management practices involve optimizing fertilizer types, application rates, timing and placement to align N supply with crop N demand, crop management practices include straw incorporation, cover cropping, and crop diversification and soil management practices includes Conservation tillage practices, such as reduced or zero tillage. In addition, the potential of enhanced nutrient recycling and of dietary change to close the gap between just and safe N boundaries is discussed.

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# Water content and pH thresholds jointly control the distribution pattern of soil nitrogen in arid zone ecosystems.

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**ABSTRACT**

The nitrogen (N) cycle in arid regions is highly sensitive to the degree of aridity. However, there remains considerable uncertainty regarding the distribution process between ammonium nitrogen ($NH_4^+$-N) and nitrate nitrogen ($NO_3^-$-N) in natural ecosystems. This knowledge gap limits our ability to predict the functional changes of ecosystems under intensified aridity. This study, based on large-scale field observation data from 120 plots spanning 2,000 kilometers east-west and 1,600 kilometers north-south in the typical arid region of Xinjiang, China, covering the complete desert-grassland-forest ecosystem, utilized linear mixed-effects models and structural equation models to analyze the spatial patterns, environmental thresholds, and driving pathways of nitrogen forms. The results showed that across the entire regional scale, soil inorganic nitrogen was dominated by $NH_4^+$-N, but gradually shifted to $NO_3^-$-N dominance during the transition from forest/grassland to desert. Along the aridity index gradient (AI = 0.03 to 0.5), both $NH_4^+$-N and $NO_3^-$-N exhibited significant nonlinear transitions, and these transitions had critical thresholds at soil water content (SWC = 0.5%) and soil pH = 8.55. Random forest and structural equation models indicated that $NH_4^+$-N was mainly regulated by soil chemical environment (pH) and vegetation productivity, while $NO_3^-$-N was dominated by water-salt conditions (SWC, EC) and climatic factors. Overall, the distribution of soil nitrogen forms in arid regions is driven by the "water-pH" synergy, which is the core mechanism for the process transformation of nitrogen cycling in arid ecosystems along the dry-wet gradient. This study quantified the environmental thresholds of this phase transition, not only filling the knowledge gap in the transformation mechanism of nitrogen forms in arid regions but also providing precise scientific basis for formulating ecosystem nutrient management and vegetation restoration strategies in response to climate change.

**Keyword:**Arid zone; Nitrogen form; Environmental threshold; Ecosystem

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# Tracing nitrogen and carbon controls on urine-induced $N_2O$ emissions in regenerative and continuous grazing systems

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## ABSTRACT

Regenerative grazing systems, such as mob grazing, are characterized by short-duration, high-density stocking followed by extended rest periods, in contrast to conventional continuous grazing, where animals graze the same area for prolonged periods. Such system promises improvements in animal productivity, carbon sequestration and soil health, but their impact on emissions of the greenhouse gas nitrous oxide ($N_2O$) is unknown, raising concerns about whether such systems exacerbate or mitigate nitrogen losses from grazed grassland ecosystems, which are major agricultural sources of $N_2O$. This study investigated how contrasting grazing histories influence the temporal dynamics of urine-induced $N_2O$ emissions by using a combined 13C and 15N approach. We hypothesized that (1) grazing history would influence both the magnitude and timing of urine-induced $N_2O$ emission peaks, and (2) these temporal patterns may be further shaped by carbon availability, including contributions from plant-derived versus soil background carbon.

The experiment was conducted under fully controlled conditions as a greenhouse incubation using soil samples from two pastures with the same soil type but contrasting long-term grazing histories (continuous grazing and mob grazing). Ryegrass was grown in the soils to simulate plant–soil interactions. 15N-labelled synthetic urine (200 and 400 kg N ha-1 equivalent) was applied to quantify the contribution of urine-derived nitrogen to $N_2O$ emissions during both grazing and rest periods. Gas sampling was carried out on days 1, 2, 3, 6, 8, 10, 14, 21, 28, and 49 following the urine application, while destructive soil sampling was conducted on days 1, 3, 7, 14, 28, and 49 to monitor changes in soil inorganic nitrogen and other properties. The results revealed that soils with a continuous grazing history consistently exhibited early $N_2O$ and $^{15}N$-$N_2O$ peak fluxes and raised $N_2O/(N_2+N_2O)$ ratio2–3 days after urine application, whereas soils from the mob grazing management showed delayed peaks and ratio at approximately 7–8 days. These contrasting peak timings were reproducible and independent of N application or seasonal grazing status, suggesting that grazing history exerts an influence on the timing of peak $N_2O$ production and raises the possibility that factors beyond nitrogen transformations alone—such as carbon availability—may contribute to the observed emission dynamics.

To further investigate mechanisms underlying these consistent temporal differences in $N_2O$ emission peaks, a dual stable isotope experiment was conducted to explore whether peak $N_2O$ production was primarily associated with plant-derived C inputs or with SOM-C, since denitrification is a heterotrophic process, the supply of electron donors from carbon sources can directly affect $N_2O$ production and reduction. In this experiment, plants were pulse-labelled with $^{13}C$–$CO_2$, while the nitrogen fate was simultaneously traced using $^{15}N$-labelled synthetic urine. Results show that the C source related to $N_2O$ production and reduction varied with both grazing management and with time after the addition of $^{15}N$-urine.

Current results demonstrate that the timing of peak $N_2O$ fluxes varies depending on the grazing management. This is related to the source of C respired, suggesting different C utilisation during denitrification. These findings enhance our understanding of the regulation of $N_2O$ emissions from regenerative grazed systems, which can help inform their management for greenhouse gas mitigation and C sequestration.

# Role of particulate organic matter accrual in affecting $^{15}N$ fate to grain corn comparing long-term vs. first-time vs. no cover cropping

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**ABSTRACT**

Long-term cover cropping increases soil organic matter (SOM); however, the effect of cover crop duration on nitrogen (N) uptake by subsequent crops remains unclear. We hypothesized greater N uptake by grain corn (*Zea mays* L.) with long-term cover cropping, due to both cover crop decomposition and increased mineralization of particulate and mineral-associated organic matter (POM and MAOM). To test this hypothesis, we introduced a novel experiment by growing cover crops for the first time on a sub-set of no cover crop plots to facilitate comparisons among long-term, first-time, and no cover cropping treatments. We applied $^{15}N$ (12 kg N $ha^{-1}$) in microplots after cover crop emergence and traced it into cover crops, corn, and soil (0–90 cm depth). During cover crop season (late fall and following spring), long-term and first-time cover cropping had about double the total $^{15}N$ recovery in cover crop biomass and soil, compared to no cover cropping where only 30% of $^{15}N$ applied was accounted for, indicating both long-term and first-time cover cropping are equally effective at reducing potential overwinter N losses. At corn harvest, long-term and first-time cover cropping had approximately ten times greater $^{15}N$ recovered in soil than in corn biomass, indicating cover crops likely contributed more to soil organic N retention than soil inorganic N supply to subsequent crops. Moreover, piecewise structural equation modeling demonstrated that POM, but not MAOM, was the main soil mineral N source for grain corn in the sandy loam site. Overall, our findings demonstrated that SOM accrual with long-term cover cropping boosted mineral N supply to the subsequent crop than either first-time or no cover cropping, as well as increased grain yield relative to no cover cropping, clearly underscoring that building-up SOM is critical for enhancing N availability in agroecosystems.

# Integrating Soil Remediation and Land Valuation: Evidence from the UK and China under an Environmental–Economic Framework

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**ABSTRACT**

Soil contamination presents a persistent challenge to sustainable land use and urban regeneration. While remediation technologies have made it technically feasible to restore contaminated sites, their economic implications for land valuation remain insufficiently understood. This paper develops an integrated environmental–economic framework to examine how remediation cost, contamination risk, and location jointly influence land value. Drawing on comparative evidence from the United Kingdom and China, the study demonstrates that perceived contamination risk exerts a stronger negative impact than remediation cost, while location significantly moderates value recovery. The findings also highlight the decisive role of institutional frameworks in shaping market outcomes. By bridging soil remediation and land valuation, this research contributes to the development of a green valuation approach that incorporates environmental considerations into property appraisal.

Highlights

- Soil contamination significantly reduces land value.
- Contamination risk has a stronger impact than remediation cost.
- Location moderates the economic effects of contamination.
- Institutional frameworks shape land value recovery patterns.
- A green valuation framework is proposed for sustainable land use.

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# Unpacking Cause and Effect in Soil Health Science

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**ABSTRACT**

Soil health has become a cornerstone concept for advancing sustainable agricultural management. Great progress has been made in the last decade in understanding how environmental drivers and management practices influence soil health and how soil health indicators affect key ecosystem services such as crop yield and soil water storage. These are fundamentally causal questions that seek to identify true cause–effect relationships rather than simple correlations. In this presentation, I argue that our community should more explicitly embrace causal inference. I will explain why causality is central to both the definition and assessment of soil health, and how causal diagrams can clarify the relationships among soil health, its drivers, and ecosystem services. Using case studies, I will show how a causal inference framework could be applied to account for confounding factors and reveal the true effects of cropping systems on soil health. I will also discuss how this framework could reveal the causality between soil health and crop yield. These examples highlight the potential of causal inference to enhance both theoretical clarity and empirical rigor in soil health science.

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# Microbial Biodiversity and its role in Soil Health in Mediterranean Agricultural Landscapes of Sicily

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**ABSTRACT**

Over the last decade, large-scale surveys have significantly advanced our knowledge on soil microbial biodiversity and elucidated the main environmental drivers shaping its global distribution. Continent-scale studies (e.g., Maestre et al., 2015; Labouyrie et al., 2023; Christel et al., 2024) consistently identified soil pH, organic carbon content, and land use intensity as key determinants of microbial diversity and functionality. Despite their ecological and agricultural importance, Mediterranean areas remain markedly underrepresented in these surveys. Sicily, characterized by pronounced environmental heterogeneity and diverse agricultural practices, lacks comprehensive datasets that integrate microbial community profiles with soil physicochemical properties and degradation dynamics. This data gap hinders the development of reliable microbial indicators for soil health in a region highly vulnerable to climatic variability and anthropogenic pressures.

To fill in this gap, the SOILS4MED project employed a factorial experimental design (2×2×2) encompassing soil type (Chromic Luvisols *vs.* Vertisols), land use (arable *vs.* tree crops), and degradation status (degrading *vs.* stable/improving). A total of 200 topsoil samples (0-20 cm) are being analyzed using amplicon sequencing targeting bacterial 16S rRNA gene and fungal ITS region, alongside of physicochemical parameters, pH, SOC, C/N ratio, texture, bulk density and $CaCO_3$. The study investigates how soil characteristics, land use, and degradation influence the structure, composition, and potential functions of microbial communities, and microbial diversity. By correlating taxa with environmental variables and applying functional and network-based analyses, the research aims to elucidate the ecological relationships underpinning soil ecosystem functions. This integrated approach seeks to identify microbial indicators responsive to ecological gradients typical of Mediterranean soils. The organization and connectivity of microbial communities may serve as early-warning indicators of soil health, while network-based measures can reveal community complexity and resilience. Ultimately, the findings aim to strengthen soil health monitoring frameworks and promote sustainable soil management strategies across Mediterranean landscapes.

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# From fragmented legacy data to predictive hydraulics: PTF4MED for Mediterranean soils

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**ABSTRACT**

The Mediterranean Region is a climate and food-security hotspot where soils face converging pressures: land degradation, low organic carbon, water scarcity and rapidly intensifying droughts. Yet, despite decades of field campaigns and laboratory analyses, soil hydraulic information in the region remains scarce because most legacy measurements were never translated into operational water retention functions. Pedotransfer functions (PTFs) offer a cost-effective way to unlock this "sleeping" legacy, but widely used PTFs are largely trained on northern European data and perform poorly in the environmentally heterogeneous Mediterranean basin.

We addressed this gap by compiling a truly Mediterranean hydro-pedological dataset, integrating thousands of records from legacy sources in Italy, Greece, Jordan, Spain, Tunisia, Morocco, Egypt, Lebanon and Syria. Two complementary datasets were built: HYDRO-GRAV (n = 6,468; gravimetric water content) and HYDRO-VOL (n = 3,943; volumetric water content). On this basis, we developed PTF4MED, a family of pseudo-continuous hydro-PTFs that predict gravimetric or volumetric water content at any user-defined matric potential using only clay, sand, organic carbon and matric potential as inputs. Multiple Linear Regression and Multilayer Perceptron (MLP) models were trained with 100-iteration stratified Monte Carlo cross-validation; MLPs consistently outperformed linear models, with HYDRO-GRAV MLP achieving RMSE = 0.060 ± 0.002 and $R^2$ = 0.780 ± 0.016. When benchmarked against 12 widely used international PTFs, PTF4MED delivered higher accuracy at most investigated matric potentials, particularly around field capacity (−33 kPa) and permanent wilting point (−1,500 kPa).

PTF4MED is, to our knowledge, the first pseudo-continuous hydro-PTF framework specifically designed for the Mediterranean Region. Developed within the SOILS4MED initiative, it illustrates how harmonized legacy data can be converted into regional-specific inputs for modelling, irrigation planning and drought-risk assessment, strengthening the capacity of Mediterranean countries to manage soil and water in a rapidly changing climate.

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# The Soil Indicator Dichotomy – finding the common ground

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**ABSTRACT**

Soil indicators are widely used while assessing aspects of soil such as health, quality, and function. Indicators help land managers, agricultural industries, and policy makers focus on how soils support particular goals, such as producing food, or filtering water. There are many indicators, gained in varied ways from simple observation to complex technical procedures. Crucially, indicators must be matched to their intended purpose and contextualized. The value of indicators depends on the unique attributes of farming systems, industries, and soils. Consequently, soil indicators are designed for different actors—farmers, agronomists, consultants, industry representatives, and researchers across diverse enterprises, production systems, and agroecological settings.

Some core indicators may be universally valued; however, a common set of indicators does not meet the needs of all actors. Financial institutions, while aware of soil's importance to farm performance, note that soil-health metrics require clearer, more familiar terminology for lending and investment decisions. This highlights a key divide: the metrics relevant to growers and those needed by investors can differ so much that they require translation to ensure alignment.

A further challenge lies in reporting soil investments that reward "best practice" rather than bio-physical outcomes. It remains unclear whether incentives should focus on practices, outcomes, or both—understood as "lead" and "lag" indicators. Communicating the distinction between these approaches and linking them within a unified framework will help bridge current gaps in soil indicator expectations across sectors.

We propose a Strategic Performance of Soil Management (SPSM) Reporting System to integrate these varied needs. Its purpose is to enable consistent reporting that is useful for land management decisions while also supporting investors such as financial institutions. This framework can help recognize and reward good soil management through incentives, including favorable lending terms.

**Acknowledgments**

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# From Soil Enzymes to Policy: The Soil Health BR Platform as a National Tool for Climate-Smart Agriculture in Brazil

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**ABSTRACT**

Since 2020, Brazil has adopted soil bioanalysis (SoilBio) technology, an initiative that integrates two key soil enzymes—arylsulfatase (ARYL) and β-glucosidase (GLU)—into routine commercial soil analysis (Mendes et al, 2024). This approach has allowed SH monitoring at the farm scale by combining chemical and biological indicators within a Soil Quality Index (SQI) framework, which includes three soil functions: (F1) nutrient cycling, based on ARYL and GLU activities; (F2) nutrient storage, based on soil organic carbon (SOC) and potential cation exchange capacity (CEC); and (F3) nutrient supply, based on $Ca^{2+}$ , $Mg^{2+}$, $K^{+}$, P, pH, $H+Al^{3+}$, and $Al^{3+}$ .

SoilBio technology has been made accessible for farmers through the training of commercial soil testing laboratories by the Brazilian Agricultural Research Corporation (Embrapa) SoilBio Network. The reliability of the results across the country is ensured by the nationwide standardization of methods and protocols and appropriate proficiency testing.

In November 2025, at COP 30, Brazil launched the "Soil Health BR Platform: Resilient Soils and Sustainable Agricultural Systems", which already includes more than 56,000 samples collected across 1,450 municipalities. Built in partnership with 33 commercial laboratories integrated through a digital system, the platform consolidates dispersed laboratory data into a dynamic national database. This structure supports climate-smart agriculture, guides evidence-based public policy, and fosters the development of low-carbon food systems.

The resulting database combines enzymatic and chemical analyses with information on location (municipality level), crop type, and soil texture. Processing this dataset for large-scale SH assessments provides an unprecedented overview of soil health conditions across Brazilian regions, helping identify trends, patterns, and emerging challenges. In doing so, it contributes directly to improving the sustainable management of agricultural landscapes.

By making this national soil health database publicly available and continuously updated, Brazil takes an important step toward transparency and data-driven action.

The initiative targets policymakers, government representatives, the private sector, NGOs, international organizations, farmers, and researchers, as well as all those interested in sustainable agriculture, climate, and soil. Monitoring soil health stands as a strategic tool to ensure sustainable productivity and climate resilience, and the public release of the platform represents a landmark contribution to global agendas on climate, soil, and food security.
**Keywords:** arylsulfatase, β-glucosidase, soil quality, SoilBio Technology, geospatial analysis, soybean

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CNPq and FAPDF

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# Comprehensive Assessment and Spatial Variability of Soil Health in Fruit Sugarcane Fields ofWengyuan, Northern Guangdong

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## ABSTRACT

Wengyuan County is the most important fruit sugarcane producing area in northern Guangdong. However, excessive and indiscriminate fertilization has caused soil health problem in some fields. The typical sampling points were identified by field survey in seven producing areas in Wengyuan, and the key soil properties such as bulk density, moisture content, pH, organic matter (OM), available nutrients and exchangeable ions were determined in this study. ArcGIS spatial interpolation was used to establish a soil health evaluation system and reveal county-wide sugarcane field soil quality status and spatial variability. The results showed that the sugarcane field soil is mainly sandy soil with loose texture. The average soil pH is 4.77, and the average contents of available N (AN), available P (AP) and available K (AK) are 184.45, 249.86 and 237.69 mg $kg^{-1}$, respectively, which are in an excessive state. The contents of OM and exchangeable Mg are 18.78 g $kg^{-1}$ and 0.54 cmol $kg^{-1}$, respectively, which are in a deficient state. The overall health level is below average, with serious acidification and unbalanced nutrients proportion. Spatially, the bulk density and AP were decreased from northwest to southeast, the moisture content, OM, exchangeable Ca and Mg content increase gradually from west to east, pH increases from the middle to the east and west, while AN and AK decrease from northeast to all around in Wengyuan. In view of these problems, we put forward comprehensive improvement strategy, including soil-test-based scientific fertilization, crop rotation, soil acidification adjustment and nutrient supplementation, in order to achieve the balance of soil nutrients and the sustainable development of fruit sugarcane industry in Wengyuan.

**Key words**: Fruit sugarcane; Soil health; Spatial variability; Improvement strategy



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# Study on the Trade-offs between Cultivated Land Soil Health and Cultivated Land Soil Quality

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**ABSTRACT**

**ABSTRACT:** The sustainability of cultivated land systems relies on the synergy between current production functions and long-term ecological resilience. To clarify this relationship in the undulating plain area of northern Liaoning, this study constructs an evaluation index system that respectively characterizes the current quality conditions and long-term sustainable health potential of cultivated land. Through a comparative analysis of Network Analysis (NA) and Principal Component Analysis (PCA) for index weighting, coupled with bivariate spatial autocorrelation, this study reveals the complex spatial dependence mechanisms between cultivated land soil health and cultivated land soil quality. The results indicate: (1) NA significantly outperforms PCA in weight stability and evaluation accuracy, proving more suitable for analyzing the complex internal relationships within cultivated land systems; (2) Soil health is predominantly at fragile and sub-health levels (combined 53.99%), while soil quality is predominantly classified as third or fourth grade; (3) Globally, a weak negative spatial correlation exists between soil quality and soil health; (4) Local analysis identifies four spatial patterns: High-High (H-H) Excellent Zone, Low-Low (L-L) Degraded Zone, Low-High (L-H) False Fertility Overdraft Zone, and High-Low (H-L) Improvement Potential Zone. This study provides a solid spatial decision-making foundation for developing a future-oriented zoning governance system for cultivated land resources by accurately identifying their spatial synergy and trade-off relationships.

**Keywords:** Cultivated soil health; Cultivated soil quality; Network analysis; Bivariate spatial autocorrelation; Undulating plain area in northern Liaoning

**Supporting figures:**



Fig. 1 Distribution Map of Soil Health Levels

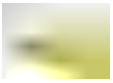


Fig. 2 Distribution Map of Soil Quality Grades



Fig.3 Bivariate Moran's I Results of Cultivated Land Soil Health and Cultivated Land Soil Quality

**Acknowledgments**

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# Unveiling Soil Vitality in Morocco: A Comprehensive Evaluation of Soil Health Indicators in a semi-arid area

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**ABSTRACT**

The present work aims to evaluate the soil health status in a semi-arid area of Morocco (El Koudia station) using the Cornell Comprehensive Assessment of Soil Health (CASH), in order to assess the soil's potential to promote crop productivity and environmental sustainability. The study comprehensively examined 11 soil health indicators encompassing physical, chemical and biological soil properties, including bulk density (Bd), available water capacity (AWC), wet aggregate stability (WAS), pH, active carbon (AC), organic matter (OM), soil protein index (SPI), soil respiration (Resp), phosphorus (P), potassium (K), and minor elements (Mg, Mn, Fe, and Zn).

In the El Koudia site, identified as a chromic Luvisol, Bd is moderate at 1.41 g/cm³ indicating a still balanced soil structure that supports good root development, with significant variations in AWC (0.17 g/g) and WAS (12.3b, 9.6a, and 9.1a for 0-5 cm, 10-15 cm, and 5-10 cm layers respectively). In contrast, most chemical indicators showed few differences related to depth, except for pH, P, and Zn, which varied significantly in the topsoil. Biological indicators revealed significant variations across depths, indicating richness, particularly in the upper layers with an active microbial community. Based on the Cornell soil health assessment, the El Koudia site reveals significant limitations, notably in WAS, SPI and pH. These challenges, resulting from prolonged intensive tillage and continuous mono-cropping practices, pose potential risks to agricultural production and ecological sustainability, emphasizing the necessity of efficient soil management strategies. With an overall score of 48, the El Koudia site fall in the medium range indicating room for improvement. Through this study, the comprehensive assessment of soil health of El Koudia site provides opportunities to deepen our understanding of soil quality, pinpoint targeted management interventions, and monitor progress over time.

***Keywords:*** *Assessment, soil health, indicator, sustainability, tillage, score.*

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# The Soil Health Indicator: A Scalable, Rapid Assessment Tool Linking Soil Science to Agricultural Sustainability

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**ABSTRACT**

Conventional soil testing has long focused on fertilization and yield optimization, typically relying on a limited set of chemical parameters. However, sustainable land management requires a broader understanding of soil multifunctionality and its contribution to essential ecosystem services, including food production, water purification, climate mitigation, and biodiversity support. These services are directly linked to several UN Sustainable Development Goals. Despite this relevance, comprehensive soil health testing remains underutilized due to challenges in complexity, standardization, and cost.

To address these limitations, we developed a rapid and scalable soil health assessment tool—the Soil Health Indicator (SHI)—combining Near-Infrared Spectroscopy (NIRS) with multi-nutrient 0.01 M $CaCl_2$ and ICP-MS extraction. This approach enables simultaneous evaluation of physical, chemical, and biological indicators, including bioavailable heavy metals, thereby generating a far more complete soil profile than traditional testing methods that measure only a small subset of soil properties. The SHI thus provides a high-resolution, multi-indicator dataset that is suitable for large-scale monitoring programs and practical land user-level decision-making for agriculture but also for nature, forest and urban areas. The tool demonstrated high analytical performance, with coefficients of determination ($R2 \geq 0.88$) for most key soil parameters when compared with References laboratory methods. The approach has been evaluated across more than 15 countries, including regions in Europe, China, New Zealand, and Vietnam, covering a wide range of soil types and land-use systems

The SHI can be integrated with crop-protection residue analysis and soil physical indicators related to structure and moisture regimes, forming a comprehensive dataset for Living Lab case studies. Within these Living Labs, scientists, advisors, and farmers co-design sustainability strategies. Farms that meet defined thresholds for ecosystem services—including soil health—can be designated as “Lighthouses,” serving as replicable examples for similar agroecological zones. This threshold-based approach shifts policy focus from prescriptive management rules to performance-based sustainability outcomes.

The SHI’s scalability, rapid turnaround, and broad indicator coverage make it a practical tool for widespread adoption. Its transparency and simplicity support land user engagement, while its scientific robustness ensures relevance for policy, monitoring, and research. By enabling comprehensive soil health assessment at scale, the SHI provides a pathway to operationalize soil science for sustainable agriculture and the SDGs.

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# Assessment and Long-Term Monitoring of Soil Quality in France and its Overseas Territories

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**ABSTRACT**

The RMQS framework is based on standardized sampling protocols and analytical methods, ensuring spatial and temporal comparability and supporting evidence-based public policies related to sustainable land management, climate change mitigation, and environmental and human health. A second national sampling campaign is currently underway in mainland France and the French West Indies, enabling robust assessment of long-term soil health trends.

To address the diversity of environmental conditions, the metropolitan RMQS model has been adapted to Overseas Territories, particularly tropical rainforests and mangrove ecosystems. In Guadeloupe, the monitoring network includes 60 sites covering a wide range of soil types and land uses, including agricultural systems, pastures, forests, and protected natural areas. The program benefits from strong local partnerships, notably with the Guadeloupe National Park, reinforcing its scientific relevance and societal impact. An extension of the network to 40 additional sites in Martinique is planned from 2026.

Soil health assessment encompasses a broad set of indicators, including soil biodiversity, pH, water holding capacity, contaminants, and soil organic carbon. Soil samples are archived in the European Soil Sample Repository (CEES), creating a unique soil legacy resource that supports future research, methodological harmonization, and long-term environmental assessments.

By integrating harmonized monitoring, soil information systems, and long-term soil archiving across temperate and tropical environments, the RMQS program provides a transferable framework for soil health monitoring that bridges science, policy, and society, contributing to sustainable soil and landscape management at national and international scales.

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RMQS2 : deuxième campagne métropolitaine, 2016 – 2027, Version 3, INRA, US 1106 InfoSol, Orléans, France.

# Building a Grower Facing Portal for Soil Health Assessment and Decision Making

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**ABSTRACT**

In North America, access to soil health testing for growers through commercial soil laboratories has been limited by laboratories' ability to consistently interpret soil health measurements. In addition, growers who wish to compare soil health results over time must use the same laboratory, as measurement methods vary across laboratories. To address these challenges, the Soil Health Institute (SHI) is developing an online soil health portal that will allow growers and advisors to create accounts, enter field-level management data, select sampling locations, print sample labels, ship samples to SHI partner laboratories, and receive regionally relevant soil health interpretations. Partner laboratories will be trained to analyze SHI's suite of essential soil health indicators, (soil organic carbon concentration, 24-hour carbon mineralization potential, and aggregate stability measured through slaking image analysis), along with particle size analysis and soil pH to support interpretation of results. Following initial training, partner laboratories will participate in an annual proficiency testing program to ensure that data generated across laboratories are interoperable and comparable. Resulting data will be modeled alongside SHI's benchmarking dataset, enabling growers to assess how their soil health compares with that of regional peers in similar cropping systems and to understand the potential trajectory of soil health improvement. In addition, collected management data will be used to calculate continuous soil health management indices, allowing growers to track how changes in management practices align with soil health principles over time. The portal will also provide regionally relevant educational resources and contact information for technical assistance to support growers and advisors seeking to improve soil health. By improving access to standardized, interpretable soil health data and regionally relevant educational materials, this platform will give growers and advisors greater confidence to implement management changes and evaluate their impacts on soil health.

**Acknowledgments**

Past and current SHI staff contributed greatly to the creation of the soil health portal

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# A Comparison of Two Soil Health Assessment Frameworks

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**ABSTRACT**

Soil health assessment frameworks are employed worldwide to translate soil measurements into benchmarks to inform management decisions, yet there have been few efforts to evaluate how different frameworks influence interpretation at regional scales. Using a single, management-explicit dataset from the Greater Golden Horseshoe region of Ontario, Canada, we compared two soil health assessment frameworks: the Soil Health Assessment and Plan (SHAP) approach and the Soil Health Institute (SHI) regional benchmarking approach. We evaluated the sensitivity and redundancy of the indicator sets, their responsiveness to management, and the influence of sampling design and statistical inference on farmer-level outcomes.

Carbon and nitrogen indicators exhibited substantial redundancy, while aggregate stability measured by image analysis was orthogonal to carbon indicators and robust to organic amendment effects. Management sensitivity varied among indicators, with all indicators except for aggregate stability by wet sieving showing management effects after accounting for inherent soil properties. Both frameworks displayed broadly similar rank ordering of scores and proportions of References, but interpretation of results varied between frameworks, with SHAP providing relatively poorer soil health scores compared to the SHI framework.

Categorical texture grouping in SHAP produced discontinuities in scoring at texture boundaries of up to 29 points (100-point scale) and did not significantly or practically reduce the influence of inherent soil properties. The SHI framework accounted for inherent soil properties using continuous variables, which did minimize texture effects for two out of three indicators. Most importantly, for the sake of interpretations, simulations demonstrated that the distribution of management types in the parent database influenced SHAP scoring curves. Conversely, the inclusion or References soils significantly influenced References-based benchmarks in the SHI framework. These findings show that outcomes of soil health assessment depend on framework design and assumptions as well as the soil measurements themselves. Explicit consideration of pedological context, experimental design, representation of soil management, and statistical inference is essential for ensuring soil health assessment is interpretable and actionable.

# The role of SOILS4MED project in promoting soil information in the Mediterranean and a unique case study from Apulia Region in Italy.

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**ABSTRACT**

SOILS4MED shares the vision that is an urgent need to enhance in the Mediterranean the availability of soil data and information (SDI) and to harmonize methods towards standardized soil information systems as enabling conditions to protect and improve soil health and support policies to achieve land degradation neutrality and accomplishment of SDGs. SOILS4MED has the following objectives: 1) engage with stakeholders in line with the Living Lab approach and raise awareness on benefits deriving from increased investment in SDI; 2) develop policy relevant integrated indicator sets and monitoring protocols; 3) validate the protocols in study areas representing major agro-ecological regions and soil types, generating the first region-wide harmonized soil health dataset; 4) demonstrate the capacity of the produced SDI, integrated by legacy soil data, to feed state-of-the-art tools to support sustainable land management and to enhance soil mapping; and 5) implement standardized country-based SIS for effective management and use of SDI. SOILS4MED builds on the relevant work done by the FAO's Global Soil Partnership and the Joint Research Centre (JRC) of the European Commission and will provide support to the compilation of the Mediterranean Soil Atlas, supported by the JRC and FAO.

Part of the activities of the project is the Salento study site in Apulia Region in Italy where the soil samples are confronted with legacy soil data collected 30 years ago. The purpose is to assess the state of soil health and quantify changes in soil chemical, physical and biological properties. The area was badly affected by the bacteria Xylella Fastidiosa that has desiccated thousands of olive trees causing a severe environmental and socio-economic crisis, hence it is essential to develop sustainable soil management strategies to recover soil health and the oliviculture sector in the region.

**Key words:** Mediterranean, soil information, soil health, Apulia Region

SOILS4MED project is part of PRIMA programme supported by the European Union.

# Nature-based Solutions for Transforming Smallholder Agriculture in Highland Areas of Northern Thailand

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**ABSTRACT**

In the past, some highland areas of Thailand were continuously used for shifting cultivation, particularly maize production for animal feed, leading to severe soil degradation and deforestation. Tea Oil and Plant Oils Development Center, the Chaipattana Foundation has implemented Nature-based Solutions (NbS) based on the principle of mutual support between people and forests to restore degraded land and promote sustainable agriculture. Smallholder farmers were encouraged to shift from maize to oil tea (*Camellia* spp.), a shrub suitable for sloping land that functions as a cover crop to reduce soil erosion and improve soil and water conservation (Liang et al., 2017).

Although oil tea leaf litter accumulated on the soil surface, decomposition was limited due to low soil biological activity. Despite relatively high nutrient levels in the topsoil, plant nutrient uptake remained constrained. A Fishbone Diagram (6M) analysis suggested that soil management strategies should rely on resources accessible to farmers. Field experiments showed that applying microbial products developed by the Land Development Department improved soil health and increased oil tea yield by up to 42%.

**Acknowledgments**

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# Application of Dredged Soil Resource Utilization in Mangrove Habitat Improvement

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**ABSTRACT**

Drawing on more than 30 marine ecological protection and restoration projects, CCCC Guangzhou Water Transport Engineering Design and Research Institute Co., Ltd. has cumulatively completed over 4,600 hectares of mangrove restoration. Focusing on the key entry point of beneficial reuse of dredged material, our company has continuously carried out research on critical technologies for coastal wetland ecological restoration, successfully overcoming key technical bottlenecks such as mangrove habitat creation in deep-water tidal flats and the improvement of dredged silt into suitable planting soil. Our company has formulated technical standards such as the Technical Guidelines for Mangrove Habitat Creation Using Dredged Material, providing replicable and scalable technical pathways and engineering paradigms for the synergistic advancement of beneficial reuse of dredged material and coastal ecological restoration. This presentation will focus on the technical pathways for beneficial reuse of dredged material , engineering application outcomes, and standardization efforts, and will systematically share our institute's practical experience and research achievements in soil ecological restoration and coastal wetland protection.

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# Cover Crop-Driven Anaerobic Soil Disinfestation Enhances Weed Suppression and Collard Greens Productivity

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**ABSTRACT**

Anaerobic soil disinfestation (ASD) is a sustainable pre-plant soil management technique, utilizing labile carbon incorporated into the soil profile, while relying on a consortium of soil microorganisms to create anaerobic conditions, suppressing soilborne pathogens and weeds while enhancing crop production. Traditional ASD relies on industrial inputs like chicken manure and molasses, which increase costs and carbon footprint, but the potential of cover crop "CC" residues as alternative carbon sources has not been thoroughly investigated in collard green (*Brassica oleracea* var. *viridis*) production. This study evaluated sunnhemp (*Crotalaria juncea*) and sorghum-sudangrass (*Sorghum bicolor* × *S. sudanese*) as *in situ* carbon sources for ASD in a greenhouse experiment. A factorial randomized complete block design tested four residue treatments (sunnhemp "SH", sorghum-sudangrass "SS", their 1:1 mixture "MX", and control bare-ground "BA") with three rates of conventional carbon inputs "CMM" (0%, 50%, and 100% of chicken manure at 20,000 kg/ha and molasses at 14,000 L/ha). After collecting soil and CC residues from field plots, they were mixed with CMM, saturated, and sealed in microcosms for 6 weeks, before transplanting collards to grow for 4 weeks in greenhouse conditions. Results showed that SH improved collard growth and yield while suppressing weeds without CMM. SS reduced soil pH from 6.0 to 5.3, significantly decreasing yellow nutsedge but also impairing collard vigor, likely due to allelopathy. SH and SS reduced corn spurry and eclipta weeds by 85–90% and increased collard biomass by 150–155% compared to the control, performing comparably to 100% CMM. In conclusion, SH residue effectively replaces industrial carbon sources in ASD, providing comparable weed suppression and crop growth benefits while reducing input costs. This approach offers a practical alternative for integrated weed management and enhanced crop productivity in southeastern vegetable production systems.

**Acknowledgments**

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# Changes in Soil Bacterial and Fungal Community Characteristics in Response to Biochar Treatments

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**ABSTRACT**

To optimize biochar for improving soil health, crop production, and environmental benefits, we need to study changes in soil bacterial and fungal communities as a response to biochar treatments. This will enable us to determine the effects of biochar on nutrient cycling, plant-microbe interactions, and the functional responses of soil, as well as to formulate effective and soil-specific application strategies.

We carried out pot experiments with biochar (BC), NPK fertilizer and wheat in artificial soil, investigated changes in soil chemistry and microbiomes after biochar treatments, and functionally annotated differentially represented microbes. There were some significant differences of BC addition on soil C, N, C/N, pH and extractable (ammonium lactate) Al and K (but not on extractable P). Phenotypic analysis confirmed the best growth after addition of 5% BC with fertilizers. Without fertilizers, BC decreased plant growth. Ground biochar decreased growth. PCA and other analyses showed clear changes in microbiome communities during plant growth, i.e. between the start and end of the experiments. We did not find an influence of BC addition on the diversity and richness of microbial communities, both for fungi and bacteria. Most highly present microbes represent saprotrophic, organic degraders, symbiotic and mycorrhizal species, nitrogen fixing and antibiotic producers.

Future work might include expanding the work to long-term field trials using natural soils and potentially additional crops.

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# Productive Grassland: Influence of Mixture Composition on Yield and Nitrogen Response Efficiency in a Temperate Region

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## ABSTRACT

Reducing reliance on synthetic nitrogen (N) fertiliser without compromising yield in intensively managed grasslands is essential for mitigating environmental impacts such as nitrous oxide emissions and nitrate leaching. Nature-based solutions such as multispecies mixtures of grasses, legumes and herbs can help achieve this goal. They can enhance yield (Grange *et al.*, 2021) and N use efficiency (Obasoro *et al.*, 2025) compared to grass monocultures receiving 150 and 100 kg N $ha^{-1}$ $yr^{-1}$ more N input, respectively.

In 2023, 50 experimental plots were established at AFBI Crossnacreevy on sandy silt loam soil to investigate how variations in mixture composition influence yield and N response efficiency (NRE). Proportions of three functional groups (FGs: two grasses, two legumes and two herbs) were systematically varied. Plant communities ranged from one to three FGs, with each FG proportion divided equally between the two species of that FG. Plots were randomly assigned one of two N fertiliser treatments: 0 and 150 kg N $ha^{-1}$ $yr^{-1}$ (0N and 150N). In 2024, six harvests were conducted to determine annual dry matter yield (DMY). Annual NRE was calculated for the 150N plots as the increase in herbage N offtake above the mean of the 0N treatment, divided by the amount of N fertiliser applied, and expressed as a percentage.

In both N treatments, higher legume proportions in mixtures increased DMY. The equi-proportional six-species mixture at 0N increased DMY by 75% and 47% ($P < 0.001$) compared to the two-species grass- and herb-only communities at 150N, respectively. NRE, calculated for the 150N treatment, was higher in the two-species legume-only community compared to the grass- and herb-only community ($P > 0.1$). However, when legumes were mixed with grasses in the six-species mixture, NRE was 13% lower than the grass-only community ($P > 0.1$), which may reflect N transfer from legumes to grasses, lowering the relative N offtake response to N fertiliser application.

The six-species mixture of grasses, legumes and herbs produced higher DMY at 0N, but its NRE at 150N tended to be lower than the grass-only community at 150N, likely reflecting enhanced N availability from legumes. This highlights the capacity of multispecies mixtures to enhance yield even at lower synthetic N inputs, potentially reducing the environmental impacts of intensive grassland systems.

**Acknowledgments**

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# Synergistic Mitigation of Crop Rhizosphere Soil Microbial Nitrogen Limitation by Maize-Peanut Intercropping and Straw Return in Black Soil Region: Insights from Extracellular Enzyme Stoichiometry

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## ABSTRACT

Soil extracellular enzyme stoichiometry is a key indicator for assessing microbial resource limitation. However, the characteristics of microbial resource limitation in rhizosphere soil under the combined measures of intercropping and straw return remain unclear. This study was conducted in the black soil region of Northeast China to explore the effects of intercropping and straw return on soil nutrients, microbial biomass, extracellular enzyme activities, and their C∶N∶P stoichiometry in the rhizosphere of maize and peanut. The average vector length (VL) of extracellular enzymes in the rhizosphere soil of maize and peanut was 1.68 and 1.57, with vector angles (VA) of 37.80° and 34.67°, respectively. This indicated that soil microorganisms in the rhizosphere of crops in the study area were co-limited by carbon (C) and nitrogen (N), and the N limitation of microorganisms in peanut rhizosphere was more significant. Compared with maize monocropping, the combined measure of intercropping and full straw return increased VA by 5 degrees, effectively alleviating rhizosphere soil N limitation. Compared with monocropping, the combined measure of intercropping and full straw return significantly increased the microbial biomass carbon-to-nitrogen ratio (MBC∶MBN) by 5.20% and the nitrogen-acquiring enzyme activity (NAG+LAP) by 32.59% in peanut rhizosphere soil. For maize rhizosphere, the promoting effects were more pronounced: carbon-acquiring enzyme activity (BG) increased by 94.23%, phosphorus-acquiring enzyme activity (AP) increased by 41.77%, while the ratios of carbon-to-nitrogen acquiring enzymes (BG∶(NAG+LAP)) and carbon-to-phosphorus acquiring enzymes (BG∶AP) increased by 44.40% and 35.38%, respectively. The extracellular enzyme C∶N∶P stoichiometry in the rhizosphere soil of maize and peanut was 1.33∶1.29∶1.00 and 0.89∶1.29∶1.00, respectively. In maize rhizosphere soil, the activities of carbon and phosphorus acquiring enzymes (BG, AP) were extremely significantly positively correlated with total nitrogen (TN), total phosphorus (TP), and MBC∶MBN ($P<0.01$). In peanut rhizosphere soil, the above enzyme activities, as well as VL and VA, were extremely significantly positively correlated with soil organic carbon (SOC), TN, TP, TN∶TP, SOC∶TP, and microbial biomass carbon, nitrogen, and phosphorus ($P<0.01$), with an overall stronger correlation than that in maize rhizosphere. Redundancy analysis (RDA) further revealed that microbial biomass nitrogen (MBN) was the key factor affecting microbial nutrient limitation, with an explanation rate of up to 54.6%. In conclusion, the extracellular enzyme stoichiometric characteristics of rhizosphere soil varied significantly between different crops. Intercropping had a stronger impact on rhizosphere microbial nutrient limitation than straw return, and their synergistic effect could significantly alleviate rhizosphere microbial N limitation by enhancing BG activity.

**Keywords:** Soil nutrients, Microbial biomass, Extracellular enzyme activity, C∶N∶P stoichiometry, Microbial nutrient limitation

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# Assessing rhizosphere and root traits of maize varieties under drought in integrated greenhouse and field experiments

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**ABSTRACT**

As climatic processes become increasingly unpredictable, drought events have emerged as one of the biggest challenges for modern maize (*Zea mays* L.) production. Particularly during early development stages, limited water availability can reduce important agronomic traits such as plant growth and grain yield. In commercial agriculture hybrid maize varieties are primarily grown to ensure high and predictable yields. However, these varieties often show low tolerance to fluctuating environmental conditions, making them more susceptible to substantial losses. To better understand and ultimately improve the drought resilience of maize varieties, it is essential to study the underlying mechanisms and adaptive strategies associated with root and rhizosphere traits.

To explore these questions, we combined a controlled greenhouse experiment with field trials to explore both controlled and real-world variability. In a high-throughput phenotyping setup, six varying maize genotypes – including landraces and modern hybrids - were grown under five distinct water regimes and two contrasting soil types. This allowed us to track differences in growth dynamics, root traits, and physiological responses. During the following growing season, two of these genotypes were further tested under varying field conditions in Bavaria. In the field trials monocropping and mixed-cropping systems were included, to examine how interactions between varieties influence water use, root development, and overall plant performance.

By linking results from both approaches, we aim to identify genotypes that consistently perform well under drought and to determine the root and rhizosphere traits that underpin this resilience. These findings should help guide breeding and management strategies and emphasize the potential of maize landraces as valuable genetic resources for developing varieties adapted to increasingly dry and variable climates.

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# BIOCHAR AND COMPOST AS NATURE-POSITIVE SOLUTIONS TO SEMI-ARID AGRICULTURE: MULTI-LEVEL ASSESSMENTS OF SOIL HEALTH, NUTRIENT CYCLING, AND GREENHOUSE GAS EMISSIONS

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**ABSTRACT**

Biochar and compost applications have been promoted as a nature-positive approach to improving soil health and reducing greenhouse gas (GHG) emissions; however, significant uncertainty exists in quantifying their role in soil health and productivity, nutrient retention and loss, as well as soil nitrous oxide ($N_2O$) emissions in depleted semi-arid soils. We evaluated soil health, C, N, and P cycling, and net GHG emissions through a series of laboratory, greenhouse, and field experiments. Laboratory assessment of soil $N_2O$ emissions from soils amended with biochar prepared from diverse agricultural and forest biomass shows that pinewood pyrolyzed at 700 °C (PB700) was the most efficient in reducing $N_2O$ emissions, with 24% less total cumulative $N_2O$ emissions than CTRL. In contrast, cattle manure pyrolyzed at 500 °C (CM500) resulted in 74% greater cumulative $N_2O$-N emissions than CTRL (10.4 mg kg $^{1}$) and 102% to 107% greater emissions than plant-based agricultural biochars. It also showed the largest labile nitrogen pool ($N_l$) in CM500 among all biochars, and the cumulative $N_2O$ emission was positively correlated with $N_l$ ($r = 0.85$; $p < 0.001$). Soil C mineralization was 5.5–17.6% lower with pinewood pyrolized at 500 °C than with others. Greenhouse assessment of soil health, C, N, and P cycling shows that an increase in SOC was positively related to biochar C, surface area, and pore volume. In the field experiment, biochar application reduced cumulative $N_2O$-N and $CH_4$-C emissions by 85% and 43%, respectively. Soil moisture was positively correlated with $N_2O$-N emissions ($R^2 = 0.39$), while soil temperature had the strongest correlation with $CH_4$-C emissions ($R^2 = 0.37$). Overall, biochar-treated soil had the lowest (43% less) net global warming potential (GWP) compared to compost-treated soil and 22% lower than CTRL. Biochar emerged as a promising soil amendment for semi-arid soils, enhancing C and N cycling, lowering GHG emissions, and GWP.

**Keywords:** Soil health, greenhouse gas emissions, soil carbon sequestration, drylands

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# Synergistic Water Retention and Growth Promotion Mechanism of Tamarind Seed Polysaccharide-Sodium Alginate-PGPRs Hydrogel in Dry-hot Valley Areas

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## ABSTRACT

With the intensification of global climate change and the impact of human activities, the ecological degradation problem in arid and semi-arid areas has become increasingly serious. In particular, the dry-hot valley areas represented by the Jinsha River, Nujiang, and Yuanjiang river basins in my country are facing severe ecological degradation problems such as poor soil, poor water retention, and severe erosion [1] due to high temperature and drought, low and concentrated precipitation, huge evaporation, and distinct dry and wet seasons [1]. As one of the key industries that support human survival and development, agricultural production is a core issue in the field of sustainable agricultural development. Endophytic plant growth promoting rhizobacteria (PGPRs), as an environmentally friendly microbial agent, provides a sustainable solution in enhancing plant stress resistance (such as drought, salinity) and promoting plant growth [3-4]. However, its survival rate and colonization ability are significantly affected by direct application due to the harsh environmental conditions of hot dry valleys. This study aims to develop a new, environmentally friendly hydrogel based on Tamarind Seed Polysaccharide (TSP) and sodium alginate (SA) to encapsulate PGPRs to improve its activity and function in the fragile ecological environment of hot dry valleys, and to enable efficient application in harsh environments. By utilizing the water retention properties of tamarind seed polysaccharide (water retention rate > 90%), the sustained release properties of sodium alginate (sustained release period ≥ 14 days), and the biological activity of PGPRs (survival rate > 80%), green and pollution-free microbial water retention growth promoters are developed to improve the stress resistance of crops, improve soil, and assist ecological restoration in hot dry valley areas. At the same time, China's abundant tamarind resources (annual output in Yunnan, Guangxi and other places >100,000 tons) are used to promote the high-value utilization of agricultural waste and realize the application of tamarind seed polysaccharide in the agricultural field for the first time.

We optimized the formula of TSP-SA-$CaCl_2$ hydrogel and systematically characterized its physical and chemical properties, including swelling ratio, water retention rate, mechanical strength and microstructure. The functional response mechanism of the TSP-SA composite hydrogel under simulated hot dry valley conditions (temperature 30-45°C, relative humidity 20-40%) was used to explore the growth-promoting mechanism and soil improvement effect of the composite hydrogel. Successfully developed 1-2 tamarind seed polysaccharide-

sodium alginate-PGPRs composite hydrogel formulas with good water retention properties, certain gel strength, high PGPRs encapsulation rate, high bacterial survival rate, and suitable for dry and hot valley areas. Elucidate the water and nutrient slow release dynamics and PGPRs C5 activity maintenance mechanism of tamarind seed polysaccharide-sodium alginate-PGPRs composite hydrogel under drought stress, and reveal its coupling mechanism to promote crop growth by improving the rhizosphere micro-area water and fertilizer environment.

In this study, for the first time, tamarind seed polysaccharide interacts with sodium alginate and calcium chloride to form a polymer hydrogel with a three-dimensional network structure through electrostatic attraction, ionic cross-linking and hydrogen bonding, and uses it as an encapsulation carrier for rhizosphere growth-promoting bacteria PGPRs. Through flat plate, potted and field experiments, the water retention and growth-promoting effect of polymer-encapsulated PGPRs hydrogel in various crops was explored, and its synergistic water retention and growth-promoting mechanism in hot dry valley areas was clarified, laying a theoretical foundation for the development of new and efficient agricultural preparations. It solves the outstanding problems of fragile ecological environment, drought and water shortage, and limited agricultural development, and provides a low-cost, environmentally friendly ecological restoration and agricultural production increase technical solution, which provides a theoretical and practical basis for the development of sustainable agriculture in arid and semi-arid areas, and helps rural revitalization and ecological civilization construction.

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# Connection between fertilizer inputs, soil microbiota and common bean agronomic performance

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**ABSTRACT**

The common bean is considered the most important grain for direct human consumption. This crop is demanding in soil fertility, and its needs can be met with the use of different sources of fertilizer, such as chemical or organic. Fertilizers, in turn, affect soil microbiota, which performs several functions such as nutrient cycling and availability, and promotion of plant growth. Therefore, the aim of this work was to explore the effect of fertilization on common bean cultivation, soil nutrient content, and variation in soil bacterial taxonomy. Field experiments were conducted in a latosol area previously cultivated with soybean. For this study, common bean was grown without fertilization, with chemical fertilization (NPK 5:20:10), and with organic fertilization made from poultry litter containing 1.75% nitrogen. Organic fertilization was applied 20 days before sowing due to its slow mineralization. Cultivation occurred in the main season, sowing on November 5, 2021, and in the second crop season, sowing on January 21, 2024, using a randomized block design with four repetitions. Soil samples were collected at 0, 30, and 60 days after sowing (DAS) in each growing period. These samples were analyzed for chemical composition, microbial biomass carbon, basal respiration, and metabolic quotient. At 30 and 60 DAS, plant samples were collected to analyze plant tissue composition. Another soil sample was collected 60 DAS for soil metataxonomic analysis. For this analysis, amplicon sequencing of the hypervariable V4 region of the 16S rRNA gene was performed. Sequencing data were processed and analyzed on the EMBL MGnify platform. When plants reached harvest maturity, yield components were analyzed. Different fertilization treatments did not show significant differences in soil chemical parameters, plant tissue composition, and yield components in both tested seasons. This is probably due to the short evaluation period and the adequate soil conditions before the experiments were conducted. On the other hand, biological parameters were affected. Proteobacteria, Acidobacteria and Actinobacteria were the predominant phyla, and Candidatus *Udaeobacter*, *Sphingomonas*, *Bradyrhizobium* and *Pseudolabrys* were the predominant genera, regardless of treatment or growing season. However, organic fertilization showed greater diversity (Shannon index). In the second crop season, which is warmer and promotes greater microbial reproduction and activity, microbial communities were more complex, especially with organic fertilization. More complex networks result in greater resource efficiency, improving the stability of microbial communities. This shows that even in a short time, organic fertilization can improve the resilience of microbial communities by increasing their interactions and helping to prevent the loss of soil quality.

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# Effect of Biogenic Synthesized Nano Sulphur on growth, yield and quality of Soybean

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## ABSTRACT

Soybean (Glycine max L.) is one of the world's most important oilseed and protein-rich legume crops, contributing significantly to global agricultural economies, food industries, oil processing sectors, and livestock feeding systems. The design, manipulation, and application of nanoscale materials are all part of the cutting-edge and innovative field of nanotechnology (Ali *et al.* 2014; Agrahari and Dubey 2020). The Greek word "nano," which literally translates to "dwarf," is used to characterize materials that have at least one dimension of less than 100 nm. Nanotechnology is now present in every facet of daily life (Zulfiqar *et al.* 2019). It has increasingly turned to green or biogenic synthesis routes for nanomaterials, as these methods offer milder reaction conditions, reduced environmental footprint and the potential for biocompatibility when compare to the conventional chemical and physical methods (Antunes Filho *et al.,* 2023). In particular plant extract made synthesis of nanoparticles has become a preferred route because plant phytochemicals (flavonoids, terpenoids, alkaloids, polysaccharides) act both as reductants converting precursors into elemental or ionic nanomaterials, and as stabilizers or capping agents preventing aggregation (Huang *et al.,* 2007; Raj & Trivedi and Soni, 2022).

Nanotechnology has emerged as one of most dynamic areas in modern science due to its wide applications in medicine, agriculture, energy, and environmental remediation. While physical procedures emit harmful byproducts that harm the environment, chemical approaches use hazardous precursors to create nanoparticles. Therefore, it is imperative to employ eco-friendly, environmentally safe methods for the synthesis of nanoparticles (Bhardwaj *et al.,* 2020).By strengthening crop protection, boosting nutrient management, and fostering environmental sustainability, nanotechnology has enormous potential to transform agriculture (Sivarethinamohan and Sujatha, 2021).

In order to solve these problems, nano-engineered sulfur, also referred to as nano-sulphur or NS and consisting of particles typically smaller than 100 nm, has emerged as a game-changing technology. Because of their high surface-area-to-volume ratio, improved solubility, and better soil-plant interface interactions, these nanoparticles facilitate more effective sulfur transport and assimilation than bulk forms of S (Wang *et al.,* 2022; Mahajan *et al.,* 2023). For the production of proteins, lipids, vitamins, and compounds that improve plant flavor, sulfur is essential. Crop yield, seed quality metrics, and the amount of sulfur in seeds are closely related (Zenda *et al.,* 2021). Because of their special qualities, such as their large surface area and increased reactivity, nanomaterials are perfect for a variety of agricultural uses, such as controlling plant infections and releasing fertilizer slowly (Goswami *et al.,* 2022).

In order to create nanoparticles that can lower metal ions, scientists are constantly investigating different bacteria, fungi, and plants (Bansal *et al.,* 2014; Duhan *et al.,* 2017). The process is biofabrication of nanoparticles when any biological material or its byproduct is used to create the nanoparticles. These make use of bacteria and their extracts, fungi and their cell-free extracts, plant tissue extracts, and plant materials and their crude and solvent-specific extracts, whether organic or aqueous. Different metal and nonmetal salts are used to test these extracts. The bio fabrication process becomes somewhat uncontrollable when the biochemical content of extracts is derived from bacteria, fungi, animal tissue, or plants (Bansal *et al.,* 2014).Due to their distinct physicochemical and biological characteristics, including intense antibacterial activity, high surface reactivity, and prospective application in fertilizers, insecticides, and medication formulations, sulfur nanoparticles (SNPs) have garnered significant interest among the different nanomaterials. Sulfur nanoparticles are traditionally produced via physical and chemical processes that frequently need hazardous byproducts, significant energy consumption, and toxic reagents. Green or biogenic synthesis techniques employing plant-based biomolecules have been proposed as sustainable, economical, and environmentally friendly substitutes to address these shortcomings.

Using leaf extracts from four medicinal plants that demonstrated antibacterial activity with $Na_2Sx$, the SNP was synthesized. $Na_2Sx$ combines with sulfuric acid in an acidic environment to produce visible yellow precipitates. (Paralikar *et al.,* 2017). According to Akl M. Awwad et al. (2015), sulfur nanoparticles were successfully made from sodium thiosulfate in the presence of Albizia julibrissin fruit extract at room temperature. The final product was described as highly crystalline sulfur with high purity, a spherical shape, an average particle size of roughly 20 nm, and a particle size distribution between 10 and 100 nm.

Soybean (Glycine max L.) is a globally important oilseed crop that requires adequate sulfur for protein synthesis, lipid metabolism, and improved seed quality. However, sulfur deficiency is now widespread due to continuous cropping, resulting in reduced soybean yield and nutritional value. Conventional sulfur fertilizers often show low solubility, slow oxidation rates, and poor bioavailability, limiting their effectiveness for modern soybean production.

Nanotechnology has emerged as a promising tool to enhance nutrient delivery, but physical and chemical methods of nanoparticle synthesis generate hazardous by-products, require high energy, and pose environmental and health concerns. Green synthesis using plant extracts offers an alternative, yet challenges such as variability in phytochemical composition, lack of standardization, and limited understanding of nanoparticle–plant interactions hinder its widespread application.

Therefore, there is a critical need to develop and evaluate biogenic sulphur nanoparticles as an efficient, sustainable, and environmentally safe sulphur source for soybean crop. This study seeks to address these limitations by exploring green-synthesized sulphur nanoparticles and assessing their potential to improve soybean growth, yield, and sulphur-use efficiency.

The present investigation were conducted during *kharif* season of 2023-24 and 2024-25 at Akola, India. The experimental soil was medium deep black, swell shrink, montmorillonites mineralogy with clay texture and classified under Vertisol. It is located in the subtropical zone at 22°42' North latitude and 77°02' East longitude, with an elevation of 307.42 m above sea level and average annual rainfall is around 846.5 mm (33.33 inches).The climate of Akola is semi-arid and characterized by three distinct seasons viz., summer being hot and dry from march to May, warm and humid monsoon from June to October and winter with mild cold from November to February. Most of the rainfall received from south-west monsoon. The total rainfall received during the cropping season was 592.8 and 813.0 mm with 28 and 37 rainy days in the year 2023-24 and 2024-25, respectively. SNPs were prepared by using typical parts of plants such as pods, leaves, peels, barks and fruits. Due to multifarious phytoconstituents present in the plant extract and behaves as herbal reducing, capping and/or stabilizing agents, therefore there is no requirement to involve external pernicious stabilizing/capping substances.

**Synthesis of SNP's**

Sulfur nanoparticles (SNPs) were synthesized by dissolving 3.2 M of sodium thiosulfate (25 mL, $Na_2S_2O_3$) in 50 mL of neem (Azadirachta indica) leaf extract, followed by continuous stirring for 5 minutes at room temperature. The mixture was then diluted to a final volume of 100 mL using sterile distilled water. Subsequently, hydrochloric acid (HCl) was added dropwise under gentle stirring to facilitate uniform sulfur precipitation. In the presence of neem leaf extract and acidic conditions, sodium thiosulfate undergoes a disproportionation reaction, yielding elemental sulfur and sulfonic acid, according to the following reaction:

$Na_2S_2O_3 + 2HCL \rightarrow 2NaCl + S + SO_2 + H_2O$

The suspended sulfur particles obtained were separated by centrifugation at 1000 rpm for 5 minutes and then repeatedly washed with sterile distilled water to remove any biological materials. The sulfur nanoparticles after purification were dried in a vacuum at 80°C for 2 hr. The product was light yellow powder used for UV-Vis, NTA, Zeta potential, TEM, XRD, and FTIR analysis. The field experiment was laid with six (06) treatments and four (04) replications in Randomized Block Design (RBD). The treatment details were $T_1$: GRDF through urea, DAP and MOP, $T_2$: $T_1$ + Foliar application of 25 ppm nanosulphur at 30 and 45 DAS, $T_3$: $T_1$ + Foliar application of 50 ppm nanosulphur at 30 & 45 DAS, $T_4$: $T_1$ + Foliar application of 75 ppm nanosulphur at 30 & 45 DAS, $T_5$: GRDF + 30 kg S/ha (Bentonite sulphur) and $T_6$: Absolute control. Note: RDF is 30:60:30 N:P:K Kg $ha^{-1}$. In all the treatments RDF will be applied through Urea, DAP and MOP (S free), FYM application @ 5t/ha at the start of experiment.

**Structural and Stability Analysis SNP**

The SNP indicated the absorption maxima at 215 nm under UV- Visible light, size of nanoparticles is 86.22 nm was observed by NTA analysis. The stable SNP's were confirmed by average zeta potential value of -21.8 mv and standard deviation of 9.56 mV these values confirmed the stabilization of nanoparticles. The high negative zeta potential values for sulphur nanoparticles synthesized from A. *indica* indicated their strong stability characterization of SNP. The transmittance peaks were observed at 3445.98 $cm^{-1}$ represented the presence of N-H stretch of amines and amides,1641.49 $cm^{-1}$ C=O groups of aldehydes and ketones,1386.88 $cm^{-1}$ C-H stretch of alkanes,1126.48 $cm^{-1}$ represented presence of C-N stretch of amines and amides .The other minor peaks at 1018.46 $cm^{-1}$,650.04 $cm^{-1}$,480.30 $cm^{-1}$ and 421.46 $cm^{-1}$ were assigned to C-O alcoholic stretch C-H of alkenes ,aliphatic chloro- and aliphatic iodo-compounds respectively were present in capping layer and stabilization of sulphur nanoparticles showed on FTIR analysis. The miller indices were assigned to a specific bragg's diffraction angle at 2 theta as given here .The XRD spectrum indicated the typical miller indices for SNP's of Bragg's 2 theta values of 113 (15.38), 222 (23.07), 026 (25.83), 313 (28.66), 044 (31.39), 317 (37.03), 062 (42.78), 515 (47.75), 357 (51.23) and 175 (53.96).The miller indices indicated the formation of crystalline SNP's.(Joint committee on powder diffraction standard file no.04-0836) were showed in XRD analysis.

**Effect of SNP on growth, yield and quality of soybean**

The plant height and number of branches $plant^{-1}$ at 30 DAS is significant and highest were recorded in GRDF + 30 kg S/ha Bentonite sulphur. The plant height and number of branches $plant^{-1}$ at 45& 60 DAS is significant and higher were recorded in GRDF through urea + Foliar application of 75 ppm nano sulphur at 30 & 45 DAS. The Dry matter accumulation (g) at 45 & 60 DAS is significant and higher were recorded in GRDF through urea + Foliar application of 75 ppm nano sulphur at 30 and 45 DAS. The chlorophyll content index (mg/g) at 30 & 45 DAS is significant and higher were recorded in GRDF through urea + Foliar application of 75 ppm nano sulphur at 30 & 45 DAS.

The number of pods $plant^{-1}$ is significant and higher were recorded in GRDF through urea + Foliar application of 75 ppm nano sulphur at 30 and 45 DAS. The number of seed $pod^{-1}$ and seed index was non-significant. The protein content and oil content was significant and higher were recorded in GRDF through urea + Foliar application of 75 ppm nano sulphur at 30 & 45 DAS ($T_4$).

**Effect of SNP on soil chemical properties and content and uptake of nutrient by soybean**

The chemical properties showed non-significant on soil pH, EC, organic carbon, available phosphorus, potassium, zinc, iron, manganese and copper, however significant effect on available nitrogen and sulphur were observed. Soil available N and S was significantly higher in GRDF through urea + foliar application of 75 ppm nano sulphur at 30 and 45 DAS. The effect of SNP on N and S content (seed and straw) were found to be significant. The effect of biogenic synthesized nano sulphur showed a significant effect on uptake of N, P and K in seed and straw with the GRDF through urea + Foliar application of 75 ppm nano sulphur at 30 and 45 DAS.

**CONCLUSION**

Based on the data generated during two years of experimentation it can be concluded that, biogenic synthesis of SNP's can suggest that many bio-constituents were present in A. *indica* leaf extract which were responsible for reduction, capping and stabilization of sulphur nanoparticles with eco-friendly nature and characterization of sulphur nanoparticle is with 86.22 nm, higher negative value of zeta potential, with different functional groups, polydispersed size and crystalline nature. Biogenic synthesis of nano sulphur application significant improved plant growth parameters, yield components and increased quality of protein and oil content. Biogenic synthesis of nano sulphur application increased the nutrient and uptake. Thus, it can be concluded that, application of biogenic synthesized nano sulphur significantly improved the growth, yield, quality, nutrient content and uptake.

**Keywords:** Biogenic nanosulphur; Soybean; Foliar application; Yield and quality improvement.

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# Enhancing Drought and Salinity Resilience in Tomato Plants Using Plant Growth-Promoting Bacillus Species from Semi-Arid Soils of Australia

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## ABSTRACT

Plant growth-promoting bacteria (PGPB) are beneficial microbes that enhance plant growth and mitigate abiotic stress. The increasing use of PGPB in sustainable agriculture highlights the necessity to elucidate their roles in improving plant tolerance to drought and salinity. This study investigated the resilience of tomato plants inoculated with PGPB, with the goal of identifying potential biofertilizer candidates. Soil samples were collected from commercial fields in the semi-arid region of Northwest Victoria and analysed for physicochemical properties. Three *Bacillus* species were isolated and identified through 16S rRNA sequencing. The isolates were screened for key plant growth-promoting traits, including 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity, nitrogen fixation, siderophore production, phosphorus solubilization, indole-3-acetic acid (IAA) production, and acid/base production. Firstly, tomato seedling growth was assessed in vitro using Murashige and Skoog medium inoculated with the three bacterial strains. The strains were subsequently applied to tomato plants grown hydroponically under controlled conditions and subjected to three levels of drought and salinity stress. After eight weeks, growth parameters were recorded. The endogenous hormones abscisic acid, IAA, salicylic acid, zeatin riboside, methyl jasmonate, and gibberellic acid were quantified in roots and leaves using a triple quadrupole mass spectrometry workflow. Statistical analyses were conducted using Minitab 19. Soils consisted of clay, sandy loam, and clay loam, with water content and organic carbon below optimal ranges, while potassium, calcium, magnesium, pH, and electrical conductivity exceeded recommended levels (based on Australian Wine Research Institute, 2023, guidelines). *Bacillus subtilis* and *Bacillus gibsonii* exhibited positive ACC deaminase activity, while *Bacillus mycoides* did not display notable plant growth-promoting characteristics. Under in vitro conditions, *B. gibsonii* significantly enhanced taproot elongation, while *B. subtilis* and *B. mycoides* significantly increased root branching. In the hydroponic experiment, significant differences were observed among treatments for shoot and root length and area. *B. gibsonii* promoted the highest plant growth under non-stressed conditions and improved root area under drought. Despite bacterial treatment, the shoot area declined with increasing drought intensity. Under salinity stress, plants treated with *B. gibsonii* and *B. subtilis* exhibited higher root and shoot areas than controls. Hormone profiling revealed distinct shifts in endogenous signalling following bacterial inoculation. In conclusion, the application of *B. gibsonii* and *B. subtilis* enhanced tomato growth under both normal and stress conditions, highlighting their potential as biofertilizer candidates for improving drought and salinity resilience in agriculture. Further studies are needed to validate their effectiveness under field conditions.

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# Optimizing Soil Health in Tropical Peatlands through Coconut-based Agroforestry

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**ABSTRACT**

Agroforestry is increasingly recognized as a nature-based solution (NBS) to promote soil health and ecosystem resilience in degraded tropical peatlands, where long-term drainage and monoculture practices have accelerated nutrient loss, and biological decline. In Indonesia's vast coconut (*Cocos nucifera*) peat ecosystems, sustaining soil quality is vital, yet empirical, quantitative comparisons of soil health across land-use systems remain scarce, particularly using integrative indices that capture biological responses like microbial biomass carbon (MBC) in drained perennials. This study evaluates soil health via the Soil Quality Index (SQI) in coconut monoculture (CMC) and coconut agroforestry (CAF) systems in Indragiri Hilir Regency, Riau, the country's largest peat-based coconut region. Field sampling targeted 0-15 cm depth across four villages (Teluk Nibung, Kateman, Sungai Danai, Manunggal Jaya), with three replicates per land-use type. A Minimum Data Set (MDS) of physical (bulk density), chemical (pH, Na), and biological (MBC) indicators was derived via principal component analysis (PCA) for additive SQI computation. ANOVA revealed significant differences ($p<0.05$) only in pH, Na, and MBC, all higher in CAF, driving superior chemical stability and biological activity. Overall SQI was 57.68% in CAF versus 46.04% in CMC, signaling enhanced resilience against subsidence and nutrient leaching. These findings affirm CAF as a superior, diversified NBS over CMC, leveraging vegetation complexity for organic matter inputs and microbial enhancement. To optimize peat-based coconut sustainability, we recommend scaling intercropping with N-fixing species and monitoring MBC thresholds, potentially stabilizing yields and minimizing emissions. These measures contribute to socio-economic sustainability by supporting smallholder resilience amid fertilizer volatility.

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# Ecological Regulation Function of Soil Microorganisms: Synergistic Effects of Arbuscular Mycorrhizal Fungi and Trichoderma in Biotic and Abiotic Stress Tolerance

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## ABSTRACT

Soil microorganisms, particularly arbuscular mycorrhizal fungi (*Rhizophagus irregularis*, AMF) and *Trichoderma harzianum* (Th), play critical roles in enhancing plant resilience to both biotic and abiotic stresses. These microbes improve nutrient acquisition, modulate immune responses, and help plants tolerate environmental stresses. This study investigates how the co-inoculation of AMF and Th enhances the resilience of two crop models—tomato (*Solanum lycopersicum*), which faces pathogen-induced stress, and licorice (*Glycyrrhiza uralensis*), a medicinal plant affected by drought stress. The findings highlight the ecological roles of these microorganisms in improving agricultural sustainability.

In the first experiment with tomato, we assessed the effects of AMF and Th on plants infected with *Fusarium oxysporum* (Fo), a common soil-borne pathogen. Both AMF and Th independently reduced *F. oxysporum* colonization, leading to a shift in the plant immune response from a jasmonic acid (JA)-dominant to a salicylic acid (SA)-dominant pathway. This immune shift, characterized by increased phenylalanine ammonia-lyase (PAL) and polyphenol oxidase (PPO) activities, resulted in enhanced disease resistance. However, while both microbes improved disease tolerance, co-inoculation did not result in an additive or synergistic effect on disease suppression, suggesting that microbial interactions may not always lead to enhanced disease control.

The second experiment focused on licorice, a medicinal plant valued for its bioactive compounds, glycyrrhizin and liquiritin. Inoculation with *R. irregularis* significantly improved licorice biomass, drought tolerance, and the production of secondary metabolites. Specifically, glycyrrhizin levels increased by 29.9%, and liquiritin production was 3.3 times higher under drought stress. Co-inoculation with *T. harzianum* further boosted glycyrrhizin yields by 93.7%, demonstrating a synergistic effect between the two microorganisms. Gene expression analysis revealed the upregulation of key biosynthetic genes, including *Squalene synthase* (*SQS1*) for glycyrrhizin and *Chalcone synthase* (*CHS*) for liquiritin. These results indicate that microbial inoculation enhances nutrient uptake and activates metabolic pathways for bioactive compound production.

This study underscores the ecological regulation functions of soil microorganisms in enhancing plant resilience to both biotic and abiotic stresses. The combined inoculation of AMF and Th significantly improved disease resistance in tomato and promoted drought tolerance and secondary metabolite production in licorice. These findings provide valuable insights into the use of microbial consortia to improve plant health and productivity, offering sustainable solutions for crop management, especially in arid and pathogen-prone environments.

# Identification of Bioplastic-associated Bacteria with Potential Degradative Activity in an Agricultural Soil System

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**ABSTRACT**

Modern agriculture is increasingly recognized as a major source of environmental plastic pollution due to the widespread use of polyethylene (PE) mulch films, which gradually fragment into microplastics that accumulate in soil and impair long-term soil health (Li et al., 2022). Biodegradable mulch films can serve as alternatives, however, achieving complete degradation of bioplastic (BP) materials in soil remains a significant challenge (Chia et al., 2021). In this study, we aim to identify soil microbial strains capable of degrading starch-based bioplastics used in biosolarization—a non-chemical pest management technique in which plastic films trap solar radiation to elevate soil temperatures, while organic amendments stimulate microbial activity and promote natural biopesticidal processes (Stapleton, 2000; Stapleton et al., 2016). We hypothesize that the selective conditions created by this system provide a suitable method to select for bioplastic-degrading bacteria. Initial *in vitro* assays show that 24 isolated strains exhibit varying starch-hydrolyzing ability based on halo diameters. These isolates were identified via 16S rRNA Sanger sequencing and characterized by colony morphology, with most belonging to the genus *Bacillus*. We are currently investigating whether these targeted microbial isolates can effectively degrade bioplastic mulch films in soil. Soil phytotoxicity will be evaluated through seedling germination assays to assess whether the resulting soil environment supports healthy plant growth. These results will provide a foundation to develop microbial inoculum to accelerate the breakdown of residual bioplastic fragments to prevent the accumulation of microplastics.

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# Soil health responses to nature-positive management regulate soil water infiltration in semi-arid agroecosystems

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## ABSTRACT

Nature-positive farming, an approach that improves crop production while increasing resilience and harmony between nature and society, is expected to enhance soil health and increase soil water infiltration. However, limited research exists on the response of diverse nature-positive farming practices on soil health and soil water infiltration dynamics. This study assessed the impact of three nature-positive farming practices on soil water infiltration and the relationship with other soil properties. For this, soil water infiltration was measured using a SATURO dual-head infiltrometer, and selected soil health parameters were measured in soil samples collected from the 0-15 cm depth of the respective fields. The results show significantly greater water infiltration rates in nature-positive practices compared to their respective controls, with infiltration rates 86% to 198% higher in nature-positive management than in the controls. Identifying factors regulating infiltration rate using linear mixed-effects model shows 70 % of the total variation in infiltration was governed by soil health indicators, with water stable aggregates being the most critical factor, accounting for 49% of the total variation. Nature-positive management could be a sustainable solution to improve soil health and security in semi-arid agroecosystems, and the stability of soil aggregates plays a critical role in improving water functions, including soil water infiltration, regardless of the nature-positive practices.

**Keywords:** Cover crops; No-tillage; Grass buffer; Dry environments; Soil health; Soil water

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# Restoring Soil Health and Managing Soilborne Pathogens in Vietnam's Intensified Coffee and Black Pepper Systems

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## ABSTRACT

Vietnam is a leading global producer of Robusta coffee and black pepper; however, decades of monocropping and reliance on nitrogen-intensive fertilisers have accelerated soil acidification, nutrient imbalances, and outbreaks of soilborne pests and diseases. From this comprehensive study, survey results revealed low soil pH levels (4.5 to 5.5), low cation exchange capacity (8 cmol(+) $kg^{-1}$), depleted organic matter, and poor soil structure. Fusarium species were widespread, Phytophthora species were found in 70% of pepper fields, and plant-parasitic nematodes were present in 75% of farms. The incidence of these pathogens was strongly linked to low pH, high nitrogen and potassium levels, and low organic matter content.

To increase soil pH, dolomitic lime (2.5 t/ha) was applied. This raised soil pH by 0.45 units and reduced exchangeable cation levels; however, it had limited short-term effects on pathogen suppression. Applying coffee husk biochar (2.5 t/ha) improved nutrient retention and soil porosity, increased arbuscular mycorrhizal fungi colonisation (16%), reduced nematodes in black pepper (33%), and lowered the incidence of Phytophthora (41%). In field trials, the most effective commercial bioinoculants reduced the abundance of *Meloidogyne incognita* (75%) in coffee and *P. capsici/tropicali*s (59%) in black pepper, whilst also inhibiting Fusarium and other nematodes.

Overall, the use of lime, biochar, and commercial bioinoculants improved soil health and reduced disease pressure on Robusta coffee and black pepper plantations. Their integration presents a promising pathway to transition Vietnam's perennial crop systems from chemically intensive practices to biologically resilient production. Future research should prioritise large-scale, multi-site trials and investigate synergistic effects among amendments, inoculants, and diversified agroecosystems.

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# Field evaluation of biochar on soil and crops in Northern Ireland (NI).

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## ABSTRACT

### Introduction

Biochar, a carbon-rich material produced by the thermochemical conversion of organic matter, has gathered great interest as a soil amendment for agriculture for its ability to enhance crop yields, improve soil fertility, and sequester carbon (Schmidt et al., 2021). However, biochar uptake in Northern Irish agriculture is low due to lack of knowledge and regional research regarding it (Cox et al., 2025). In a meta-analysis, Jeffery et al. (2017) found no positive effect on crop yields in temperate regions, associating this effect with higher inherent soil fertility. Therefore, this study aimed to measure the impact of biochar on crop performance and soil properties over 3 years in Northern Ireland on soils with contrasting fertility status.

### Method

Two field sites (moderate and low soil fertility) were set up in May 2024 with three crops cycles – spring oats (2024), winter barley (2024-25) and perennial ryegrass (2025-2026), with 4 treatments: no biochar and fertiliser control (CTRL), fertilizer (NPK) only, and biochar with fertilizer (B+NPK) and without (B0). Wood based biochar, ground to ≤2 mm, was applied once in 2024 at 5 t $ha^{-1}$, and NPK was applied annually at crop requirement rates. Soils were sampled at harvest and analysed for a range of biophysiochemical properties.

### Results

The experiment is ongoing; results from the first two years show a slight, but non-significant, increase (3.5-5%) in total carbon in plots applied with biochar compared to those without. Soil pH declined in both sites under NPK and B+NPK compared to CTRL and B0 by ~0.2 units. Only the moderately fertile site showed a change in soil nutrients, with higher soil available P in the B+FERT treatment compared to B0. Crop yield was affected by fertilization, with B+NPK and NPK showing similarly high yields, whilst CTRL and B0 were significantly lower. This experiment demonstrates that the application of fertilizer had a greater effect on soil nutrients and crop yield compared to biochar addition, in both low and moderately fertile NI soils.

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# Faba bean-wheat intercropping sustains soil water and nutrient cycling, and the carbon availability for microbes in the short term.

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## ABSTRACT

Legume-cereal intercropping systems are anticipated to play a significant role in the sustainable intensification of crop production. Their main advantage is the increased yield per area, which results from the physiological complementarity of the two companion crops. However, it has not been fully elucidated how nutrients, and carbon (C) cycling are affected by this cropping system under field conditions at different phenological stages. To address this knowledge gap, an experiment was conducted in which winter wheat and faba bean were cultivated in field under varying nitrogen (N) fertilizer doses. Soil and plant sampling covered the whole plant-growth cycle. The central hypothesis posited that co-cultivation could enhance C sequestration in soil and promote nutrient cycling closure. Various soil N and C pools were quantified, alongside the availability of the other macro- and micro-nutrients. The microbial functional potential was evaluated through the analysis of the enzyme activities and C Use Efficiency. The findings revealed that the intercropping with faba bean sustained the N cycling comparably to the normal N dose applied for wheat. Intercropping enhanced the water and nutrient availability for plants at some phenological stages, especially close to the grain-filling one. This resulted in a significant reduction in the water use efficiency under intercropping without N fertilization. The soil phosphorous mineralization potential was also stimulated. Furthermore, the results indicate that the C availability for microbes was consistently higher in all the systems compared to the sole wheat without N application. Anyway, no changes were observed in the total soil organic C concentration. Overall, wheat-faba bean intercropping demonstrated considerable potential for reducing the reliance on N fertilizers, and for improving the energy and nutrient status for soil microbial communities.

**Acknowledgments**

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# Evaluation of the soil quality improvement potential through basalt rock dust amendment

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## ABSTRACT

Improving food security strategies on highly degraded soils has become a significant challenge for South Africa. The need to secure food sources for the growing population under harsher climatic conditions is crucial. South Africa is one of the many water-scarce countries and is labeled the 30th driest country in the world. Numerous methods exist to enhance and maintain soil quality, including applying fertilizers and geological materials to the soil. Basalt has been the focus of numerous long-term studies on soil fertility. Soil plays a vital role in supporting life on Earth. They serve as a medium for plant growth, provide a habitat for soil organisms, regulate and purify water resources, and participate in various nutrient cycles, such as carbon and nitrogen, which help adapt the atmosphere. Worldwide, there is a decline in soil quality due to various anthropogenic and natural causes. If these problems can be addressed, the decline in soil nutrients, which impacts on the agricultural sector, could improve food security. One way to improve soil quality is through remineralization, which involves adding more weatherable, nutritive rock types such as mafic igneous rocks. In recent years, there has been growing interest in using basalt as a natural fertilizing agent to improve non-arable or depleted soils as an alternative to synthetic fertilizers. Previous studies have already demonstrated that using materials such as basalt can enhance the soil and crop quality. The weathering of rocks depends on factors such as the climatic conditions of the region and the physical and chemical properties of the rock. One-way soil quality can be improved by remineralization, which refers to the improvement of soil quality by adding more weatherable, nutritive rock types. Internationally, powdered rock such as basalt has been used by farmers as a natural way to improve soil root system development, increase crop yields, and aid in plant health and conditions. Basalt has given rise to the possibility of replacing synthetic fertilizers as natural amendments to improve non-arable soils. Previous studies showed that adding basalt might improve soil and crop quality. Agriculture and food production are integral to South Africa. One of the root causes of decreased food production per capita is the decline in soil quality and quantity. Contextualizing South Africa's relative scarcity of available agricultural land against the increasing demand for food production by a growing population, combined with water scarcity, it is necessary to search for innovative methods to improve the quality of soils deemed non-arable. Very little field research has been conducted on the effect of basaltic rock powder in agriculture under local South African conditions. Therefore, this project aims to determine the effectiveness of augmentation of soils with basaltic rock powder. The objective is to determine if adding powdered basalt contributes to soil fertility and increases crop yields under local climatic conditions when local basalt is used. This will be achieved by evaluating the chemical differences of local non-arable soils (sandy soils with low pH levels, low cation exchange capacity, and limited water holding capacity) augmented with powder basalt and those with no augmentation (controls).

The first part of the study focused on a comprehensive literature review to assess suitable methods and understand what methods will be fully appropriate for this study. Methods selected to achieve the aim of this project include the weathering of basalt and the elements released during a 20-week humidity cell experiment and pot field trials with different amounts of added basalt to investigate the chemical changes in the soil when augmented with basalt. In the first experimental phase, the focus was on the humidity cell experiment where basalt was used and evaluated by speeding up the weathering rate by creating an artificial environment for weathering and with the pH of the leachate measured weekly where upon Inductively Coupled Plasma Mass Spectrometry analysis was conducted on the leachates to determine the composition and amount of major and micro cations leached from the samples during the following weeks. The second part of the experimental phase of the study focused on pot field trails which were conducted by making use of two palatable grass species (i.e., *Brachiaria brizantha* and *Lolium multiflorum*) where the germination percentage, growth potential, photochemical efficiency, and elemental concentrations were analyzed when two different mixing ratios of basalt (i.e., one t/ha and three t/ha), were applied to a sandy growth medium, representative of non-arable soil. The soil characteristics that were evaluated included particle size distribution and total elemental concentrations for cations using Inductively Coupled Plasma Mass Spectrometry analysis. It was found that the concentrations of micronutrients released from the leachate were low and decreased with time, which is considered normal as nutrients released from the basalt will decrease as leaching continues. However, it was determined that, as the literature suggested, basalt has a high pH buffering capacity by increasing the pH of the leachate during the 20 weeks. When considering the macronutrients, calcium was the only nutrient that showed a significant difference from the control, meaning there were higher amounts of calcium released throughout the 20 weeks. Unfortunately, no phosphorus was detected in the leachate of the basalt samples, as suggested by the literature on similar studies done previously. The results of the micronutrients found that there was a significant difference between the control and basalt samples for vanadium, nickel, and zinc, where nickel and zinc had higher concentrations than the control leachate than that for basalt leachate. The results from the analysis indicated no clear conclusion that basalt amendment could contribute to vegetation growth on non-arable soils when considering the significant nutrients such as phosphorus and potassium, which are the primary nutrients added by synthetic fertilizers for higher production as these nutrients do not weather as quickly which makes it slower to be released for plant use. The results from the pot field trials showed some interesting findings, and it was observed that the one t/ha basalt amended samples performed better than the three t/ha and the control samples. The evidence suggests plant quality was improved to an extent, meaning that the control samples had the highest growth potential; however, when considering the germination percentage, the one t/ha basalt amended samples showed the best results. The results show significant changes and improvement in the soil and vegetation; however, the substantiation to replace synthetic fertilizers is not evident. Although the study showed that basalt can improve soil quality and fertility immediately, it is recommended that the study be expanded to evaluate the long-term use of basalt under natural field and climatic conditions to get a better view and understanding of how basalt amendment will influence soil quality and crop production in the long run.

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# Comparison study on soil layer disturbance between vertical rotary tillage and horizontal rotary tillage

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## ABSTRACT

Vertical rotary tillage, with vertical rotation axis, could reduce soil layer disturbance as compared with horizontal rotary tillage in theory, thus reducing soil structure damage and improving soil health. However, this effect has rarely been studied quantitively. This study compared soil layer disturbance quantitively between vertical rotary tillage and horizontal rotary tillage based on DEM (Discrete Element Method) and soil bin test. Firstly, a soil bin test was conducted, the soil layer disturbance was calculated by tallying colored sand that has been buried and torque requirement was determined. Then, the DEM model was established, its parameter was calibrated by comparing torque requirement of vertical rotary tillage in experiment and simulation. Results showed that overall soil disturbance of vertical rotary tillage was 82.38% in experiment and 88.32% in simulation, significantly lower than horizontal rotary tillage of 88.69% in experiment and 93.47% in simulation, verified the assumed reducing effect in soil layer disturbance by vertical rotary tillage, although a large amount of soil was also buried into deeper soil layer by vertical rotary tillage. Besides, more soil particles have been buried into the shallow layer (3-7 cm) under horizontal rotary tillage, while more soil particles have been buried into the deep layer (11-15 cm) under vertical rotary tillage. The results could provide References for sustainable soil tillage operation and help to understand the soil disturbance process under rotary tillage.

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# Identification of soil health-related problems in apple orchards: preliminary results from the Grójec Living Lab

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**ABSTRACT**

The Living Lab (LL) concept is an approach to developing innovative solutions under real settings. End users and stakeholders collaborate to create, test, and implement new products, services, or processes. Since end users are involved in the LL as active partners, the solutions developed better respond to real needs. According to this concept, 100 LLs focused on soil health are expected to be established in Europe by 2030. Five of these labs are involved in the LivingSoiLL project, which seeks to develop and implement soil health-friendly solutions for permanent crops, such as vines, olives, hazelnuts, walnuts and apples. As part of the project, the Grójec LL focuses on apple orchards, representing the largest production area for this crop in Europe. The long-term use of monoculture, fertilization that is not adjusted to the needs, the multiple use of pesticides during the growing season, and the use of heavy machinery create a risk of soil compaction, deterioration of the its structure, loss of soil organic matter (SOM), an imbalance of elements, and contamination with biogenic substances, pesticides, and trace elements, and consequently limited biological activity and many related problems. Farmers reported these problems at the initial stage of the project as well. In the next phase, soil health-related problems were verified based on 9 experimental sites (EXPS), representing medium-quality soils (usually Luvisols) and varied production modes, fertilization practices, tree varieties and their ages. The soils were sampled in spring 2025 from 3 or 5 locations per EXPS, depending on its size. In order to ensure a complex assessment, the soils were sampled both from rows and interrows. Soil samples were taken from 0-10 cm, 10-20 cm and 20-30 cm in order to determine soil bulk density, particle-size distribution, total organic carbon (TOC) and total nitrogen (N) contents. Moreover soil samples from depth of 0-20 cm were taken from the same locations for more detailed analyses, including pH, content of trace elements and bioavailable forms of P, K, Mg, and N ($NH_4$-N, $NO_3$-N), content of pesticide residues, microbiome composition (fungi and bacteria), and composition of soil sorption complex. The results indicated varied nature and severity of soil health-related problems depending on the EXPS, and showing correlation with practices applied to date. The most significant challenges concern low content and (probably) poor quality SOM, compaction and poor structure, not suitable pH and nutrient imbalances (both deficiency and strong excess). The problem of soil contamination with trace elements and pesticide residues is low. Preliminary results indicate also some problems with soil microbiome, including its structure and other characteristics.

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# Ecosystem service value of conservation tillage with cover crop-maize intercropping in the northeast black land of China

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**ABSTRACT**

Scientific evaluating the ecosystem service value (ESV) of cover crop cultivation system can provide important References for the construction of conservation tillage pattern in Northeast China. Based on experimental analysis and the theory of ecosystem service value, we calculate the ESVs of intercropping maize with gramineous cover crop ryegrass, leguminous cover crops alfalfa and hairy vetch, with maize monocropping as the control. The ESV accounting includes product supply, gas regulation, nutrient cycling, and soil and water conservation value. Results show that ESVs of cover crop-maize intercropping are higher than that of maize monocropping, nutrient cycling value is the highest, followed by product supply value, accounting for 67.32% and 29.26% of total ESV. The nutrient cycling value of cover crop-maize intercropping is higher than that of maize monoculture. The product supply value of alfalfa-maize and hairy vetch-maize are significantly higher than that of ryegrass-maize, which increased by 18.67% and 21.03%, respectively. Cover crops planting has the potential to increase the value of gas regulation services, but has little impact on the value of soil and water conservation. Considering the ESVs, intercropping with leguminous cover crops obtain the greatest benefits.

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# Agronomic constraints limit the climate change mitigation potential of winter cover crops in Europe

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**ABSTRACT**

Cover cropping is widely promoted as a promising practice for soil carbon sequestration in agricultural land. Yet, estimates for its greenhouse gas mitigation potential often overlook key factors limiting the feasibility of upscaling. As a result, current potentials may overestimate the climate change mitigation capacity of cover cropping. To support more realistic assessments, we developed and tested a framework to quantify the potential additional adoption of winter cover crops in three European countries: the Netherlands, Germany, and Spain. We addressed two key questions: (1) What is the potential for additional cover cropping based on current adoption? (2) What biophysical and socioeconomic factors influence further adoption?

Through an online survey of 321 farmers (Vidal Morant et al. 2026), we gathered data on crop rotations, current cover crop use, and agronomic constraints. The results show that most farmers already cultivate winter cover crops on at least part of their land in Germany (89 % of farmers) and the Netherlands (97 % of farmers), with only 11 % of arable land in Germany and 25 % in the Netherlands still available for further cover crop cultivation; most arable land is already covered in winter. Soil type, late harvests, and weather conditions were significant biophysical constraints to expansion in both countries. In Spain, no cover crop adoption was detected in rainfed arable systems, largely due to water scarcity. The farmers mentioned benefits such as improved soil health and reduced nitrate leaching as key drivers of adoption.

We conclude that the potential for additional carbon sequestration through cover cropping is limited. Taking into account agronomic factors is needed to bring greater realism to carbon sequestration potentials of soil management practices.

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# Enhancement of soil physical properties through the use of cover crops: A systematic review for the Argentinean Pampas

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## ABSTRACT

Frequent and intensive tillage can lead to degradation of soil physical properties. No-tillage systems have emerged as an alternative to counteract the effects of excessive tillage. However, no-tillage systems have also been associated with increases in bulk density (BD), reduced water infiltration (WI), and higher soil penetration resistance (PR), among other degraded soil physical properties. Cover crops (CC) have gained relevance due to the multiple benefits they provide and because they occupy periods in the crop sequence during which environmental resources would otherwise remain unused if the soil were left fallow. Among these benefits, improvements in soil physical conditions have been documented in several studies. However, reported results are variable and depend on edaphoclimatic conditions, CC species used, and duration of implementation. Therefore, the objective of this study was to conduct a systematic review of experiments carried out in the Argentine Pampas to assess the impact of CC on BD, PR, WI, and aggregate stability (AS). Information from 23 field-based studies was compiled and analyzed. Cover crop species were grouped into grasses, legumes, grass-legume mixtures, and brassicas. Soil depths were classified as surface (0-5 or 0-10 cm) and subsurface (5-20 or 10-20 cm) layers; and duration of CC use was categorized as short-term (1 year) or medium- to long-term (>1 year). The effects of CC on soil physical properties were evaluated using relative changes between CC treatments and the fallow (control). On average, CC inclusion resulted in 1.7% decrease in BD (0.02 Mg $m^{-3}$) and 16.4% decrease in PR (349 kPa), while increasing WI by 58.9% (45 mm $h^{-1}$) and AS by 25%. No significant differences were detected among CC species, although grasses and brassicas tended to produce greater improvements in soil physical properties. Only PR showed a significantly greater reduction in the surface layer compared to the subsurface layer. In addition, both BD reduction and WI enhancement increased with the number of years of CC implementation. These findings highlight the potential of CC as a tool for improving soil physical properties and underscore the importance of integrating CC into agricultural systems to promote sustainable soil management and enhance overall soil health in the Argentine Pampas.

# Soil Natural Productivity: A Path to Self-Regeneration and Sustainability — Empirical Insights from Hechuren's "Natural Mulching and No-Tillage"

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**ABSTRACT**

A smallholder in northern Chongqing has practiced “Huaxia Natural Ecological Farming” for 17 years, conducting a 15-year experiment in ‘Natural Mulching and No-Tillage’ on 9 mu of once-poor mountaintop land. Results show annual yields exceeding 580 kg/mu across over 70 varieties of daily essential food items: 49% grains and soybeans, 49% vegetables and fruits, and 2% oil crops. with income matching the local urban-rural average.

Drawing on Hou Guangjiong's bio-thermodynamic theory of soil fertility, natural no-tillage principles, mycological research, and paleontological evidence, we confirm that indigenous, diverse communities of soil microorganisms and soil fauna serve as the driving force and foundation of the soil life system and its natural productivity. These communities are crucial for restoring and maintaining soil fertility, enabling soil to resume its inherent role as a "renewable resource" rather than a "consumable item requiring constant repair" due to human food production.

Soil natural productivity is essentially the soil’s self-nourishing and regenerative capacity. This capacity is compromised by: (1) External chemicals, hormones, counter-natural interventions, invasive microbes, and monoculture practices, along with the loss of heirloom seeds (and their co-evolved fungal communities), all of which harm soil life and its balance; (2) Removing all weeds and crop residues, leaving soil bare and heavily tilled, causing chronic food scarcity and habitat loss for soil organisms, leading to severe decline.

Key to rebuilding this capacity: Abandoning non-natural inputs and methods while practicing diversified planting establishes natural mulching and no-tillage as the crucial mechanism for interaction, balance, and renewal in the soil life system.Its implementation activates the soil network's ancient, self-regulatory program, enabling natural pest suppression, stable nutrient supply, and system self-repair. A critical note: no-tillage is impossible without mulch, and all non-natural mulch materials must be prohibited.

Conclusion: Today, alongside global soil degradation, issues like environmental pollution, health problems, and food quality decline are prevalent. Unlike complex technological solutions that face public skepticismm, the principle of Natural Mulching and No-Tillage is rooted both in the 400-500 million-year-old "original plant-soil symbiosis" and the restarting of "soil's self-nourishing capacity," as well as in the Chinese cultural tradition of "following the Dao of nature and achieving harmony between heaven and humanity." Combined with practical farming experience, it is more visible, comprehensible, and trustworthy. With significant potential for soil and water conservation, drought and heat resilience, climate adaptation, and enhanced soil carbon sequestration, it represents a path aligned with Chinese modernization.

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# Structured Mini-Dunes (SMDs): Engineered Soil Structures for Moisture Retention and Salinity Control in Arid Sabkha Soils

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**ABSTRACT**

Arid regions, covering 41% of Earth's land, face major barriers to sustainable agriculture from water scarcity, soil salinization, and shallow saline groundwater tables on sabkha flats. This study introduces Structured Mini-Dunes (SMDs) simple, layered sand-gravel mounds inspired by natural Nabkha dunes (Al-Shukaili et al., 2028) as low-cost, self-irrigating soil structures to boost moisture retention, block salt rise, and support plant growth without external water (see Fig. 1).

Two large prototypes (150 cm diameter, 50 cm height) were built in stainless-steel tanks with controlled water tables. Each featured a 20 cm gravel base ($d_{50} \approx 1$ cm), medium sand core ($d_{50} = 0.25$ mm), thin top gravel mulch, and optional 5 cm coarse sand outer layer ($d_{50} = 0.7$ mm) on the second. Decagon 5TE sensors at 25, 50, and 75 cm depths monitored volumetric water content ($\theta_v$, stabilizing at 0.074–0.10 $m^3/m^3$) and electrical conductivity (EC < 0.06 mS/cm in upper layers) over 7 months.

HYDRUS-2D models (Fig.2), calibrated by inverse HYDRUS- 1D van Genuchten estimates ($r^2 = 0.9995$, RMSE = 0.5785), matched field $\theta_v$ data closely, especially in upper layers. Simulations confirmed higher moisture on slopes than crests (like natural dunes), vapor condensation from humid air, and minimal coarse layer benefits, allowing cheap construction with local sands.

Grass naturally grew on SMD crests post-irrigation, proving self-sustainability. SMDs offer practical tools for desert revegetation, non-halophyte farming, and arid soil management.

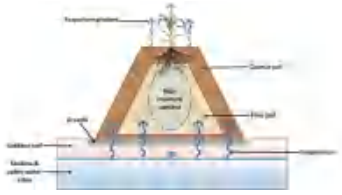


***Figure 1*** *A sketch of an axial cross-section of SMD*

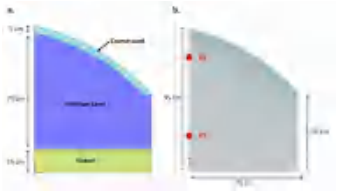


***Figure 2*** *a) The HYDRUS2D geometry and material distribution of SMD2, b) the locations of o bservation points (sensors)*

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# Soil-crop-fertilization interactions drive the effects of Fusarium oxysporum FO12 on soil properties and plant nutrition

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**ABSTRACT**

Rhizospheric microorganisms represent a promising nature-based solution to enhance plant growth, soil functionality, and stress tolerance. The non-pathogenic strain *Fusarium oxysporum* FO12 was found to promote plant growth and induce iron (Fe) deficiency responses, but its performance and mechanisms involved under different soil types, fertilization strategies and inoculation methods remain unclear. This study aimed to (i) evaluate the ability of FO12 to solubilize phosphorus (P), Fe, and zinc (Zn) from mineral sources differing in crystallinity and solubility under calcareous (CAL) and non-calcareous (NCAL) conditions, and (ii) assess the effectiveness of two inoculation methods on plant growth, nutrient uptake, and soil properties in inoculated sunflower and wheat plants grown on contrasting soils and under different fertilization strategies. To this end, the solubilization capacity of FO12 was evaluated for phosphate rock (PR) and single superphosphate (S18) (P sources), ferrihydrite (Fh), hematite, and goethite (Fe sources), and $ZnSO_4$ and ZnO (Zn sources), with or without $CaCO_3$. In addition, *in vivo* experiments were developed with sunflower and wheat grown in CAL and NCAL soils, including two inoculation methods, i.e., direct soil application (St) and seed dressing (Sd) (first experiment), and four different fertilization strategies (full or P-, Fe-, Zn-deficient nutrient solution; second experiment). Analyses included soil pH, available P, Fe, and Zn in soil, plant mineral uptake, and phytohormone profiling. FO12 successfully solubilized 6 of the 8 mineral sources compared with non-inoculated controls, mainly through pH modulation (*in vitro*). This effect was more evident when the inherent solubility [PR (+ 33.6%), and ZnO (+ 110%)] or crystallinity [Fh (+ 1950%)] of the mineral source is low. Moreover, FO12 applied via St more effectively modified soil properties and increased nutrient uptake in NCAL, whereas Sd mainly affected plant physiology, increasing jasmonyl isoleucine (+ 511%) and ACC (+ 226%) while reducing indoleacetic acid (- 39%; *in vivo*). Furthermore, St applications improved soil nutrient phytoavailability and plant nutrient uptake increased up to 26.9% (P), 51.4% (Fe), and 85.4% (Zn), especially under no nutrient constraints (NCAL, full fertilization). Besides, FO12 enhanced Fe and Zn uptake in wheat grown on CAL soil under Fe- or Zn-deficient conditions. Overall, FO12 could act as a complement to fertilization strategies via direct soil nutrient mobilization and phytohormone modulation, but its performance is crop-soil-fertilization dependent and further evaluation to define optimal application conditions is required.

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# Microbial activity and biomass in a cultivated and bioinoculated soil under water and nutritional deficit conditions

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## ABSTRACT

Microbial activities involving the production and release of metabolites that stimulate plant growth and enhance plant health are considered key factors in biological soil fertilization. Among these, Plant Growth-Promoting Rhizobacteria (PGPR) represent one ofthe most widely implemented biotechnologies. This study determined the effect of a microbial consortium on biological activity (basal respiration), microbial biomass, and various ecophysiological indices (qMic, $qCO_2$, and $qCO_2$/C-organic) in soil cultivated under water deficit and inorganic fertilization. An experimental trial was conducted in San Juan de Lagunillas, Mérida, during a crop cycle of *Allium cepa*. The experiment followed a 2x4 bifactorial design in completely randomized split plots, testing water deficit, fertilization levels (0%, 50%, 100% NPK), and inoculation with a consortium of ME01 (*Rhizobium tropici*) and Leu2A (*Bradyrhizobium japonicum*). The rhizobial consortium increased microbial biomass at 0% NPK, thereby benefiting indigenous microbial communities and improving parameters such as the microbial quotient and metabolic quotient. Conversely, the 100% NPK dose induced metabolic stress in the inoculated bacteria, reducing the ecophysiological efficiency of the microbiota. These results suggest that microbial consortia may better withstand nutrient limitation periods due to the metabolic diversity provided by interspecies variety. Possibly, under water deficit conditions, increased enzymatic activity and organic acid production, coupled with root exudates, contribute to the drought tolerance of certain plant species. The proposed microbial consortium could serve as an alternative to improve soil quality and health under low-fertilizer conditions, particularly for drought-tolerant species in semi-arid regions.

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# Cover Copping for Soil Health Improvement in North-western Canada

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**ABSTRACT**

Climate change is bringing opportunities and challenges to the agricultural sector in northern Canada, where the rate of warming is three times higher than the global rate (Bush and Lemmen, 2019). In the context of climate change, agricultural management mimicking nature is a climate-resilient approach for sustainable agriculture. Recognizing the importance of farmers' role in agricultural sustainability, the Canadian government launched the Peace Region Living Lab (PRLL, 2022-2027) to test better management practices (BMPs) and promote their wider adoption. Farmers in this Region are practicing cover cropping as one of the BMPs to improve soil health. Soils of this region are clay-rich and acidic in nature, with many challenges to crop production and soil health improvement. We assessed the effect of cover cropping on soil health in producers' farms participating in the PRLL, using soil samples collected in the first year of the project. Key soil health parameters, namely soil organic carbon (SOC) concentration, aggregate stability, and mineralizable carbon, were measured from the top (0–15 cm) soils. The SOC was determined by dry combustion using a LECO CN828 elemental analyzer. Aggregate stability was assessed using the SLAKES smartphone image-analysis application. Mineralizable carbon was quantified as $CO_2$ evolved over 24 h after rewetting air-dried soils, using an infrared gas analyzer (PP Systems' EGM-4). The SOC content ranged from 2.74 ± 0.81 to 3.18 ± 0.73% in cover-cropped farms, whereas 3.03 ± 0.57 to 4.01± 0.45% in conventionally cropped farms. Overall aggregate stability index was 0.61 ± 0.12 and did not differ between cover-cropped and conventional farms. Mineralizable carbon was numerically higher under conventionally managed farms than in cover-cropped farms, but the difference was not statistically significant. These results might indicate the fact that farmers have recently started cover cropping as a BMP to improve soil health in farms with poorer soils than the conventionally cropped, better farms. Effects of cover cropping will be re-assessed in soils collected at the end of the project period (2027) to determine clearly whether cover-cropping truly has an effect on soil health improvement in the Northwestern region of Canada.

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# Maize/peanut intercropping advantages: evidence for soil biota-mediated nitrogen transfer

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## ABSTRACT

Cereal/legume intercropping is a typical and sustainable agricultural practice. Our previous field experiments indicated that maize/peanut intercropping with appropriate nitrogen reduction achieved a trade-off among soil biological health, soil multifunctionality and crop productivity, which is related to the differences in nitrogen use between cereals and legumes. Therefore, we further analyzed the influence of soil biota at different trophic levels in the intercropping system on nitrogen transfer between maize and peanut. Based on the field intercropping experiment, we conducted a pot experiment on maize/peanut intercropping with two N applications (conventional N and 20% N reduction). Four types of barriers were used in pots, including: solid barrier (no contact), 35 μm aperture nylon mesh barrier (allow nutrients, water and soil microbes contact), 100 μm aperture nylon mesh barrier (allow nutrients, water, soil microbes and soil nematode contact) and no barrier. $^{15}$N-urea was used to analyze the contribution of soil biota at different trophic levels to lateral nitrogen transfer in maize and peanut in intercropping systems, as well as the distribution of nitrogen fertilizer among crops, soil biota, and soil in intercropping systems. Results showed that nitrogen transfer occurred in both directions between maize and peanut. Under both N applications, the total nitrogen transferred from the peanut to the maize exhibited a nematode contribution rate of 2.76–3.11%; conversely, transferred from the maize to the peanut ranged from 1.94–3.73%. PCoA analysis showed that nematode community homogeneity increased significantly with decreasing barrier restrictiveness. Under both N application levels, no significant differences were observed in soil nematode abundance or diversity, or in the biomass of maize and peanut. Decreasing barrier restrictiveness had a considerable positive relation with total $^{15}$N transfer, and both were positively associated with maize and peanut biomass. Our findings emphasized that nitrogen transfer occurred not only from peanut to maize side but also from maize to peanut side, with soil fauna facilitating nitrogen transfer between neighboring plants. Maize/peanut intercropping reduced nitrogen limitation of the system and significantly increased crop productivity.

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# Microbial solutions for reducing soil nitrous oxide emissions

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**ABSTRACT**

Nitrous oxide ($N_2O$) is a potent climate-active gas, and mitigating emissions is essential to achieving the 1.5°C climate target of the Paris Agreement. Agricultural soils are the dominant anthropogenic source of $N_2O$, yet most mitigation approaches focus on suppressing $N_2O$ production through fertilizer management, nitrification inhibitors, or reduced tillage. In contrast, nature-based strategies that enhance microbial $N_2O$ consumption remain largely overlooked [1, 2]. Recent advances have revised our understanding of the microbial $N_2O$ consumption process, revealing unexpected geochemical tolerance and previously unrecognized diversity among $N_2O$-reducing catalysts and microorganisms [3-5].

Effective microbially informed solutions — whether through managing indigenous communities or through the addition of non-native microbes (bioaugmentation) — require detailed knowledge of the ecophysiology of microorganisms capable of $N_2O$ reduction. pH is a major constraint on microbial $N_2O$ reduction, and well-studied $N_2O$-reducing microorganisms are thought to function only under circumneutral pH conditions. Here, cultivation experiments demonstrated the existence of $N_2O$-reducing acidophiles, including organisms harboring a novel $N_2O$ reductase that has been overlooked over decades. These findings substantially expand our understanding on the diversity and ecology breadth of $N_2O$-reducing microorganisms. Furthermore, cultivation experiments simulating realistic soil pH fluctuations uncovered a novel *Schinkia* species that maintains robust $N_2O$ reduction across a broad pH and salinity range, challenging the prevailing paradigm that $N_2O$ reducers endure narrow pH ranges and demonstrates that soil $N_2O$-reducing microbiomes possess substantial physiological flexibility to withstand dynamic acidity and salinity shifts. These findings provide new opportunities for leveraging microbial traits as nature-based solutions to reduce $N_2O$ emissions during climate-driven disturbance events (e.g., wetting–drying cycles), and strengthen the resilience of agricultural systems.

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# Intercropping increases soil multifunctionality potentially by increasing the abundance of functional genes: evidence from a long-term field experiment

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## ABSTRACT

Ecosystem functionality and essential services for human well-being have been degraded by intensively managed monoculture cropping systems. Intercropping may offer a means of maintaining and increasing agricultural soil multifunctionality (SMF) without reducing productivity. However, whether the maintained or enhanced SMF by intercropping is related to the potential function changes of soil microbiome driven by intercropping is poorly understood, limiting the optimization of these systems for sustainable intensification. Therefore, we investigated crop yields and SMF in a long-term field experiment established in 2009. The study evaluated soil physical structure stability, carbon, nitrogen, and phosphorus cycling, abiotic stress regulation and related functional genes under intercropping systems (chickpea/maize, faba bean/maize, oilseed rape/maize, and soybean/maize) and monocultures of the component crops at three phosphorus fertilizer application rates (0, 40, and 80 kg P $ha^{-1}$). Intercropping significantly increased crop grain yields and SMF by 27.3 and 34.6%, respectively, compared with the weighted mean values of monocultures, irrespective of phosphorus application rate. It also significantly increased the relative abundance of genes related to carbon-, nitrogen-, and phosphorus-cycling functions by 15.2%, 10.8%, and 26.3%, and the relative abundance of genes was related to weighted mean diameter of aggregates, soil compaction, total nitrogen, soil microbial biomass carbon, soil respiration, soil nitrate reductase, β-cellobiohydrolase and leucine aminopeptidase. There were synergies between soil carbon and nitrogen cycling and between physical structure stability and carbon or nitrogen cycling, and trade-offs were observed between physical structure stability and phosphorus cycling. The positive effect of intercropping on SMF was associated with enhanced enzyme activities and other soil properties and consequently increased crop yields. The results highlight the important role of intercropping in sustaining soil function and elucidate the mechanisms involved, offering novel insights into its role in reducing dependence on non-renewable phosphorus resources in agricultural ecosystems.

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# Phytoremediation Potential of Native Plant Species for Improving Soil Health in Vineyards with High Levels of Arsenic and Copper

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**ABSTRACT**

Copper (Cu) contamination in soils is an ubiquitous threat for agricultural practices using plant protection products containing this element, with vineyards achieving the highest concentrations of Cu in soils among other permanent crops in Europe (Ballabio et al., 2018). Vineyards deeply characterize the planted area in Portugal, making it a priority to investigate Cu contamination in these soils. Adding to this, in relation to other European topsoils, Portugal is one of the countries with the highest average values of Arsenic (As) (Fendrich et al., 2024).

Having said this, the case study of this work is set in a vineyard in the Douro Demarcated Region, where levels of Cu and As in soils were found to reach 132.62 and 1957.45 mg $kg^{-1}$, respectively. Trying to understand the possible consequences of such levels of Cu and As, grapevine leaves and grapes were sampled, and the levels of these elements were quantified. Results obtained for leaves indicate that they are accumulating As up to 14.40 mg $kg^{-1}$.

In order to improve soil health in this vineyard, phytoremediation emerged as a viable way to reduce the total or available contents of these contaminants in soils. For this purpose, four native plant species found already in this vineyard, which may act as hyperaccumulators or metallophytes, were used in laboratory assays to assess their capability of accumulating Cu and/or As. Preliminary results for one of the tested plants show its potential to be used as a phytostabilization strategy, due to its higher capability of accumulating these elements in roots than in shoots, with levels of Cu in roots reaching 67.23 mg $kg^{-1}$. For As, the same trend was found regarding the element's distribution in plant tissues, but with As levels in roots as high as 941.69 mg $kg^{-1}$. Overall, results so far point to a possible phytostabilization strategy of both Cu and As, which can be concomitantly applied with grapevine crops.

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# Copper–Amendment Interactions Drive Molecular and Physiological Stress Responses in Vitis vinifera

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## ABSTRACT

Copper fungicides, in continuous use since the late 19th century to fight diseases like downy mildew, have caused toxic copper (Cu) accumulation in vineyard soils. Even though Cu is an essential nutrient, in excess it can trigger oxidative stress in grapevines, harming plant health. The impact that Cu has will depend on soil properties and management, often forcing the plant to activate its antioxidant and detoxification systems to survive. Additionally, transcriptional reprogramming involving genes related to metal transport, redox homeostasis, and stress signaling can occur due to this exposure. This work intended to evaluate how Cu availability modulated by amendment application translates into molecular and physiological responses in grapevine tissues combining soil Cu dynamics, plant Cu accumulation, oxidative stress indicators, and transcriptome analyses. For this, vine plants were placed in fresh soil collected in a vineyard from the Vinhos Verdes Region of Portugal, contaminated with different concentrations of Cu and amended with a mixture of pine bark and mussel shell. Samples of leaves and soil pore water were collected after six months (T1) and one year (T2) of exposure, whereas samples of soil and roots were collected in T2. In all samples, the pseudo-total concentration of Cu was analyzed by ICP-MS after Aqua Regia extraction, whereas oxidative stress (lipid peroxidation and hydrogen peroxide) and antioxidant-related parameters (proline and glutathione) were evaluated only on the leaves. The results obtained demonstrated that time had a significant effect on the response of grapevine to the treatments and that the presence of amendments had significant effects in some of the biomarkers analyzed. Additionally, RNA-seq analysis was performed in leaves and roots at both timepoints to investigate the transcriptional mechanisms underlying the observed physiological responses. Exposure time was confirmed as a major driver of transcriptional variation, in agreement with biomarker patterns. Copper exposure induced dose- and organ-dependent transcriptional responses, whereas amendments had a stronger impact in leaves at the later timepoint. Combined Cu and amendment treatments resulted in interaction effects, particularly at T2, indicating non-additive transcriptional responses. These findings highlight organ-specific nature of grapevine responses to Cu and soil amendments and emphasize the importance of carefully addressing soil management practices as they can also shape physiological and transcriptional stress responses in poorly known pathways.

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# What matters to detect early soil health change in integrated cover crop systems?

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**ABSTRACT**

Integrating perennial cover crop (PCC) into crop rotation is widely advocated for enhancing soil health. Yet, detecting short-term (< 5 years) PCC effect on soil health remains challenging primarily due to the slow response of soil properties, which can limit its widespread adoption. To address this gap, we evaluated the effect of three years of perennial clovers in Dresden Ontario, by comparing soil health indicators across treatments (PCC and no PCC(NOPCC)) and sampling locations (in rows where the main crops were planted and between rows that were either bare soil under NOPCC or perennial clovers). Soil samples (0–15 cm depth) were collected 10 times from 2021 to 2023 where the crop rotation was corn-edamame soybean-winter wheat. We used soil microbial quantitative PCR (11 functional genes and 3 taxonomic markers), standard soil chemistry assays (5 indicators and micronutrients), and standard soil health assays (8 indicators and quality ratings with associated micronutrients) to assess temporal changes to soil health. Generally, PCC supported greater microbial functional gene abundance than NOPCC, including genes linked to nitrogen (N fixation by 26–77%) and phosphorous (P mineralization by 23–65%) cycling. Among soil chemistry and soil health assays, potentially mineralizable N and Solvita $CO_2$-C were greater with PCC than NOPCC, but limited changes were observed in soil organic matter and micronutrients. These findings indicate that microbial functional genes and labile chemical indicators are sensitive and potential early indicators of soil health change in response to management practices. Moreover, the PCC effect on soil health was more pronounced for samples collected between crop rows than within rows, highlighting the importance of sampling location in soil health assessment. The study provides a robust framework for assessing short-term soil health response to management practice, emphasizing the value of integrating soil functional genes and of PCC adoption.

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# Farming system diversification enhances land use efficiency of China's protected horticulture

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## ABSTRACT

Protected horticulture enhances land-use efficiency and food security in China. However, regional variations in farming systems and their socioeconomic impacts remain poorly quantified. Through large-scale surveys of smallholder farms (n = 246) and environmental sampling (n = 1,230) across China (longitude: 102.54°–122.97°E, latitude: 23.92°–41.97°N), we determined that this sector can deliver 37.2% of the national vegetable output on only 1.4% of China's arable land and achieve yields up to six times higher than those in open-field systems. We also identify seventeen distinct protected farming systems varying in five adaptation strategies: agroclimatic optimization, regional specialization, precise land use, use of marginal soils, and soil sustainability practices. Scenario modeling shows that by 2050, strategic production relocation to climatically suitable regions and optimization of these farming systems could further enhance land use efficiency, indicated by a decrease in land area of 7–49% while increasing farmer employment by 20–156%. Thus, diversified, small-scale farming systems represent a transformative pathway for sustainable intensification, offering scalable solutions to global food security with regional policy support.

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# Balancing Crop Yield and Environmental Risk in Chinese Greenhouse Vegetable Production Systems: Insights from Phosphorus Management

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**ABSTRACT**

Decades of continuous phosphorus (P) inputs in excess of soil P holding capacity – up to ~ 571 kg P $ha^{-1}$ versus ~ 117 kg P $ha^{-1}$ in open-field vegetable systems – has led to significant accumulations of total P (TP) and Olsen P, as high as ~ 397 kg $ha^{-1}$ and 115 mg $ha^{-1}$, respectively, in the surface soils of greenhouse vegetable production (GVP) systems in China. These figures suggest that vegetables are the primary P-consuming crops in China, given the markedly lower P application rates of 137.7 and 158.9 kg $ha^{-1}$ for wheat and rice, respectively. This substantial imbalance has saturated over 90% of surveyed GVP soils with P, especially in long-term production zones. The resulting decline in P use efficiency (PUE) increases the risk of P mobilization and eutrophication. Nonetheless, sustainable P management strategies remain largely unexplored in the Chinese GVP systems. To partially address this, a critical soil Olsen P value of 22 mg $kg^{-1}$ has been established for the five major GVP bases in China, above which the subsurface P leaching exceeds its threshold value of 0.1 mg $L^{-1}$ that can initiate eutrophication. In accordance, over 80% of GVP soils in China are at high risk for P mobilization, particularly the coarse-textured soils in northern regions. However, these thresholds must be calibrated regionally in response to the local soil properties and agricultural management practices. Alternatively, we recommend integrating organic amendments (e.g., manure, straw) as partial substitutes for chemical fertilizers to reduce long-term P accumulation. To further enhance P retention, GVP fields could incorporate tile drains equipped with P-sorbent materials. Such systems would trap P from soil leachates, enabling its recovery and reuse while preventing eutrophication risks. Collectively, these measures support sustainable P management and safeguard both vegetable production and environmental quality in China's intensively managed GVP.

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# High nitrogen-use efficiency cabbage varieties deliver a win-win of enhanced yield and reduced nitrogen discharges: comprehensive evaluation and field validation

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## ABSTRACT

Vegetables have a weak capacity to absorb soil nutrients, and their nitrogen-use efficiency is generally low, with a high amount of non-point-source nitrogen pollution. Nevertheless, there are often stark differences in nitrogen-absorption efficiency among varieties of the same vegetable species. However, research focused on screening for high nitrogen-use efficiency varieties, with the goal of reducing nitrogen pollution associated with vegetable cultivation, has been scarce. We here conducted a comprehensive evaluation of 100 cabbage (Brassica oleracea var. capitata) varieties (30 late-maturing and 70 early-maturing), assessing their yield, nitrogen absorption, and nitrogen-use efficiency. Using principal-component analysis and cluster analysis, varieties were classified into high-, medium-, and low-scoring groups. Field validation demonstrated that high-scoring varieties achieved a clear 'win-win' outcome. Compared to low-scoring varieties, their yields increased by a remarkable 47% and 76% for early-maturing and late-maturing varieties, respectively. Simultaneously, environmental nitrogen losses were curtailed in high-scoring varieties, reducing nitrogen leaching by 26%–56% and nitrogen runoff by 21%–22%. Compared with low-scoring varieties, high-scoring varieties reduced leachate nitrogen concentration by 6 to 41% and decreased leachate volume by up to 40%. By contrast, high-scoring varieties did not significantly reduce runoff volume, but they lowered nitrogen concentration in the runoff by 3 to 42%. This environmental benefit was attributed to both a decrease in leachate volume and significantly lower nitrogen concentrations in both leachate and runoff water. The underlying mechanism appears to be the superior ability of the high score varieties' aboveground biomass to absorb, transform, and regulate nitrogen, while simultaneously reducing moisture migration in the soil through coverage, thereby decreasing the residual nitrogen in the soil available for loss. Our findings establish that screening for high nitrogen-use efficiency varieties is a powerful and sustainable strategy for cleaner vegetable production, offering a practical pathway to reconcile high productivity with environmental protection without additional economic inputs.

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# Dose-Dependent Effects of Biochar on Physiological Metabolism and Fruit Quality in Tomatoes

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**ABSTRACT**

Biochar has gained significant attention as a soil amendment for its potential in sustainable agriculture by enhancing soil properties and crop productivity. This study systematically evaluated the effects of different soil biochar application rates (0%, 1%, 3%, and 5% by mass) on tomato (Solanum lycopersicum L.) physiology, growth, yield, and fruit quality. The results demonstrated that biochar amendment significantly influenced plant physiology by modifying the rhizosphere environment. Applications of 1% and 3% biochar effectively enhanced the leaf net photosynthetic rate and chlorophyll content, promoted increases in plant height and stem diameter, and facilitated the translocation of photosynthetic assimilates to fruits, thereby increasing yield. Furthermore, biochar treatment profoundly improved fruit quality metabolism by concurrently elevating the contents of soluble sugars, soluble proteins, and ascorbic acid (vitamin C), while also regulating organic acid composition, which ultimately improved the nutritional value and flavor profile of the fruits. However, the highest application rate of 5% showed a diminishing or inhibitory effect on some parameters, indicating the existence of an optimal application threshold. Collectively, our findings identify 3% as the optimal biochar application rate for synergistically enhancing both yield and quality in tomato production, providing a practical strategy for sustainable horticultural management.

**Keywords:** Biochar, Tomato, Fruit yield, Fruit quality

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# Microplastics Engineer Denitrification Hotspots in the Plastisphere to Drive Soil $N_2O$ Emissions

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**ABSTRACT**

Biodegradable plastics are widely regarded as an ideal alternative for mitigating agricultural "white pollution"; however, the potential impacts and microbial mechanisms of their microplastic residues on soil nitrous oxide ($N_2O$) emissions remain unclear. Here, we selected two typical vegetable field soils and conducted a 120-day microcosm incubation experiment. By combining $N_2O$ natural abundance isotope tracing, high-throughput sequencing, and molecular biology techniques, we systematically compared the effects of biodegradable microplastics (PBAT) and conventional polyethylene (PE) on soil $N_2O$ emissions. The results indicated that, unlike chemically inert PE, biodegradable microplastics (PBAT) significantly stimulated $N_2O$ emissions in both soils, with cumulative emissions increasing by 325% to 1094% relative to the control (CK). An isotopic dual-endmember mixing model confirmed that bacterial denitrification was the dominant pathway for $N_2O$ production. Mechanistic investigations revealed that PBAT biodegradation triggered a significant cascade effect: the depolymerization released dissolved organic carbon (DOC), potentially serving as critical electron donors for heterotrophic microorganisms. Simultaneously, a specific "plastisphere" microenvironment formed on the PBAT surface, significantly enriching denitrification functional genes *(nirS, nirK, nosZ*), with abundances far exceeding those in the bulk soil. This synergy of "carbon enrichment" and "gene aggregation" likely engineered efficient denitrification hotspots within the plastisphere, thereby driving sustained and explosive $N_2O$ emissions. This study confirms that biodegradable microplastics are not "inert bystanders" in the soil nitrogen cycle. While mitigating plastic pollution, they may pose a risk of exacerbating climate change—a trade-off that warrants high priority in future environmental risk assessments.

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# Mechanisms of nitrate accumulation in solar greenhouse with long-term high nitrogen inputs in the Loess Plateau of China

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**ABSTRACT**

The intensification of agricultural practices in the Loess Plateau region of China has led to widespread overuse of nitrogen fertilizers. Characterized by its deep soil layers and strong nitrification potential, this region promotes the rapid conversion of applied nitrogen into nitrate, which accumulates extensively within the soil profile. This substantial accumulation of soil nitrate represents a primary source of groundwater nitrate contamination. Understanding the sources and dynamics of nitrate in groundwater under sunlight greenhouse systems is therefore critical for developing targeted pollution control strategies and protecting the environment in intensively managed agricultural areas.

Through a combination of questionnaire surveys and soil sample analyses, we quantified nitrogen inputs and nitrate accumulation in a typical sunlight greenhouse system. The total annual nitrogen input was 1428 kg N $ha^{-1}$, comprising 814 kg N $ha^{-1}$ from chemical fertilizers and 614 kg N $ha^{-1}$ from organic manure (primarily cattle and chicken manure). This excessive nitrogen application resulted in a profound accumulation of nitrate ($NO_3^-$-N) in the 0-10 m soil profile, with an average reserve of 4168 kg N $ha^{-1}$ and a maximum reaching 6443 kg N $ha^{-1}$. Notably, significant nitrate levels (exceeding 20 kg N $ha^{-1}$) were detected even at a depth of 10 meters, indicating substantial leaching driven by high nitrogen inputs and intensive irrigation.

Analysis of 42 groundwater samples collected from the greenhouse area revealed an average nitrate concentration of 101 mg $L^{-1}$, with an alarming exceedance rate of 60% relative to national drinking water standards.

These findings highlight a severe risk of groundwater nitrate pollution associated with the high-input management practices in sunlight greenhouses. The study provides a theoretical foundation for implementing measures to reduce agricultural non-point source pollution and facilitates the pursuit of sustainable agricultural development in the region.

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# Dynamics of soil salinization and its combined effect with nutrients on the microbial community in solar greenhouses

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## ABSTRACT

Soil nutrient surplus and secondary salinization are common challenges in solar greenhouse (SG) systems. However, the dynamic changes of soil salinity with cropping duration and the combined effects of nutrients and salinity on the microbial community remain poorly understood. Therefore, we collected soil samples in SGs with varying cropping duration (2-3, 12-13, 21-22, and 30-31 years) and grain fields (control), and physicochemical properties, salinity, and microbial communities were measured.

Results showed that SG cultivation significantly reduced soil pH while increasing electrical conductivity (EC) and nutrient contents (mineral N, available P, available K). During the first 20 years of SG cultivation, the contents of TSS, total cations, and total anions in the topsoil exhibited a consistent increasing trend with cropping duration, peaking at approximately 11.44, 1.33, and 10.11 g $kg^{-1}$, respectively. Subsequently, all three parameters decreased significantly (Fig. 1). SG cultivation markedly altered the soil ion composition. It significantly reduced the proportional contributions of $Ca^{2+}$ and $HCO_3^-$, while progressively increasing the relative abundances of $Na^+$, $SO_4^{2-}$, and $NO_3^-$.



Fig. 1 The total concentrations and the compositions of cation (a) and anion (b) salinities in the topsoil (0-20 cm) and subsoil (20-40 cm) of solar greenhouses. Points represent mean values. Black error bars represent standard deviations.

Soil nutrients and salinity collectively reduced bacterial and fungal α-diversity. Fungal communities were less affected than bacteria. The relative abundance of salt-tolerant phyla (*Bacteroidota*, *Chloroflexota*, *Actinomycetota*) increased, while *Acidobacteriota* decreased. Our analysis revealed differing co-occurrence networks for bacteria and fungi across cultivation durations, indicating that SG practices altered potential interspecific interactions. In bacterial networks during the initial 20 years of SG cultivation, we observed a continuous increase in nodes, edges, clustering coefficient, and network density, concurrent with decreases in average path length, diameter, and modularity relative to grain fields. This indicates that SG cultivation increased the complexity of soil bacterial networks but reduced their stability (Fig. 2). Soil nutrient accumulation increased the complexity of the bacterial co-occurrence network, salinity compromised its stability.



Fig. 7 Mantel test (a) for bacteria and fungi in the topsoil (0-20 cm). Partial least squares path models (PLS-PM) show the effects of soil nutrient and salinity on the bacteria (b) and fungi (c) diversity and network.

In conclusion, long-term intensive SG management promotes nutrient accumulation and secondary salinization, altering microbial diversity, community structure, and network interactions, thereby threatening system sustainability. These findings highlight the need for optimized management practices to mitigate soil degradation in protected agriculture.

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# Organic fertilizer improves soil carbon sequestration via macroaggregate formation in intensively vegetable cultivation system

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**ABSTRACT**

Intensive vegetable production systems play a critical role in ensuring vegetable security in China and globally by maximizing yield per unit area and improving the efficiency of land and resource use. However, long-term intensive vegetable production accelerates soil organic carbon (SOC) and structural degradation loss. The application of organic fertilizer is considered a key mitigation strategy. The SOC-driven mechanisms underlying carbon (C) stabilization, aggregate formation, and mineral associations, however remain unresolved. We therefore to evaluate their effects on SOC quality and stability as well as aggregate stability using a 7-year field experiment conducted in Shenyang, China, on a Humic Cambisols soil. Four fertilization treatments, no fertilizer (NF), chemical fertilizer (CF), organic fertilizer (BF), and chemical plus organic fertilizer (CBF) were examined, with all fertilized treatments receiving an equivalent nitrogen input of 300 kg N $hm^{-2}$. The results showed that BF and CBF treatments-significantly improved soil physical properties together with macroaggregates (> 0.25 mm) formation and stability. The former also increase total and water extractable SOC concentrations of the aggregates, particularly in macroaggregates. Furthermore, the soils receiving organic fertilizer had the lowest C emissions. Structural equation modeling further revealed that enhanced macroaggregate formation was the primary pathway that strengthened SOC stability and reduced C loss. Overall, organic fertilizer effectively improved soil structure, enhanced C sequestration, and mitigated C emissions, offering a scientifically robust strategy for the more sustainable management of global intensive vegetable production system.

**Keywords:** Soil aggregation, Humic acid, Water extractable carbon, Carbon emission, Soil organic carbon

# Enhanced soil ecosystem multifunctionality and microbial community shifts following spent mushroom substrate application in protected vineyards

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**ABSTRACT**

Soil multifunctionality and microbial diversity in agricultural ecosystems are influenced by fertilization. Spent mushroom substrates (SMS) have recently been used as organic fertilizers, but their effects on soil and microbial functions in orchard ecosystems remain understood. A two-year field study was conducted to compare the different types (*Agaricus bisporus* and *Pleurotus eryngii* substrates) and application rates (equal to 975, 1575 and 2250 kg N $ha^{-1}$ $yr^{-1}$) of SMS on soil multifunctionality and microbial community properties in protected vineyard soils. The application of *Pleurotus eryngii* substrate at a N input rate of 2250 kg $ha^{-1}$ $yr^{-1}$ significantly increased soil multifunctionality by 48.04% compared to non-fertilized soil, due to reduced soil bulk density, increased soil nutrient content and enhanced soil enzyme activity. Additionally, SMS application significantly improved bacterial diversity and altered bacterial and fungal community structures, with changes positively correlated with soil organic matter content. Furthermore, SMS amendment primarily increased the relative abundances of keystone species categorized as module and network hubs in the bacterial co-occurrence network. Compared to *Agaricus bisporus* substrate, the application of *Pleurotus eryngii* substrate increased the relative abundances of organisms involved in aromatic compound degradation (38.63-71.18%) and saprotroph (3.14-4.40%), while significantly reducing pathotrophic fungi by 59.96-64.76%. It is noteworthy that Cu and Cd accumulations were increased by 7.92-52.54% in vineyard soils treated with SMS. However, the type and application rate of SMS had divergent effects on Cr and Pb accumulations, suggesting that the better microporous structure of *Pleurotus eryngii* substrate helps bind and passivate heavy metal ions depending on the element type. The contents of Pb, Cd and Cu significantly influenced the diversity and composition of soil microbes. Overall, the proper use of SMS improves soil multifunctionality, and *Pleurotus eryngii* substrate application could further enhance microbial network structures and ecosystem functions in protected vineyard soils.

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# Enhancing silicon uptake and use efficiency in Piper nigrum L. against Fusarium disease on acidic soils using Calciprill and sodium silicate

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## ABSTRACT

In highly weathered acidic soils (pH<5.5), excessive hydrogen ions ($H^+$) exacerbate the devastation of *Fusarium* disease and cause progressive decline in growth and development, yield loss, and economic shelf life of black pepper farming. A two-cycle pot study was attempted to determine the effects of Calciprill and sodium silicate to ameliorate soil acidity in addition to improving silicon (Si) uptake and use efficiency in immature black pepper vines against *Fusarium* disease on an acidic soil (Bekenu series, *Typic Paleudults*). There were eight treatments evaluated in this study where the soil was treated with Calciprill at 90% and 100% calcium saturations (C90 and C100) combined with sodium silicate at 150 kg $ha^{-1}$ (S150), whereas the soils without any amendments (C0S0) were included as control treatments to reveal how severe the pathogen can affect the productivity of immature black vines. Some of the immature vines were solely added with chemical fertilizers (NPK) and inoculated with or without *Fusarium* disease (F0 or F1) in weekly basis up to eight weeks, followed by soil analysis, plant growth measurements, and disease incidence and severity index determinations. Regardless of F0 and F1, results revealed that the soils with Calciprill and sodium silicate (C90+S150 and C100+S150) significantly ameliorated acidity by increasing soil pH, exchangeable calcium ($Ca^{2+}$), and water-soluble Si besides suppressing exchangeable acidity and aluminium compared with C0S0 and NPK. In terms of plant growth, the use of amendments also significantly increased aboveground and underground biomass production. The use of Calciprill and sodium silicate does not only improve the Si uptake and use efficiency in immature black pepper vines, but it also effectively mitigates the devastation of *Fusarium* disease by significantly reducing the disease incidence and severity compared with those vines without the amendments and those with solely application of chemical fertilizers (C0S0F1 and NPKF1). We concluded that the combined use of Calcirpill at 90% and 100% calcium saturations and sodium silicate at 150 kg $ha^{-1}$ (C90+S150 and C100+S150) were effective in improving the productivity of acidic soils and mitigating the *Fusarium* disease infection in immature black vines. Further research such as Si absorption mechanisms by the black pepper vines and economic viability studies were recommended to further validate the findings of this pot study.

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# Biochar-based microbial fertilizer enhances cucumber growth and yield by improving soil quality in protected agriculture

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## ABSTRACT

Intensive protected agriculture plays a critical role in maintaining food security and ensuring a stable vegetable supply. However, its long-term reliance on high-input management practices often accelerates soil degradation and threatens sustainable development. To explore effective green soil strategies, this study used greenhouse cucumber (Cucumis sativus L.) as a model crop and conducted a controlled field experiment to assess the impacts of Bacillus subtilis (BS), biochar (BC), and their composite biochar-based microbial fertilizer (MF) applied at four rates on soil physicochemical and biological properties, as well as crop growth and yield. An integrative Soil Quality Index (SQI) framework combining K-means clustering, principal component analysis (PCA), and canonical correlation analysis (CCA) was developed to quantify soil quality. Furthermore, partial least squares structural equation modeling (PLS-SEM) was employed to elucidate the multi-pathway response mechanisms of the soil–crop systems. The results showed that MF treatment outperformed individual BS and BC treatments in improving soil structure, nutrient availability, and microbial activity. Specifically, MF reduced soil bulk density by 10.8% and enhanced field capacity and saturated water content by 19.0% and 28.1%, respectively. It also increased available phosphorus and potassium contents by 28.9% and 39.4%, elevated urease activity by 29.1%, significantly improved microbial diversity, as evidenced by higher Shannon and Chao1 indices ($p < 0.05$). The MF achieved the highest SQI (0.79), representing a 46.3% improvement over the control, and increased cucumber yield by 24.23%, significantly outperforming the BS and BC ($p < 0.05$). Moreover, PLS-SEM analysis further revealed that MF enhanced soil quality and crop yield primarily through three synergistic pathways: strengthening water-nitrogen coupling (path coefficient, $\beta = 0.968$), activating phosphorus and potassium pools ($\beta = 0.885$), and stimulating organic matter turnover and enzyme activity ($\beta = 0.790$). Overall, this study demonstrates that MF substantially enhances soil quality and cucumber yield through multi-dimensional synergistic mechanisms. The proposed data-driven SQI framework provides a robust and comprehensive approach for quantifying soil quality dynamics, offering both a theoretical basis and practical guidance for sustainable soil management in intensive agricultural systems.

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# Organic substitution as a soil health management practice alleviates salinization and steers nematode assembly in plastic greenhouse soils

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**ABSTRACT**

Plastic greenhouse soils often accumulate salts and lose soil structure under long-term mineral fertilization, compromising soil health. We evaluated organic substitution (manure and straw) as a soil management practice and tested whether nematode community assembly links habitat restoration to soil multifunctionality. In a five-year tomato-cucumber rotation in a solar plastic greenhouse (Tianjin, China), we compared an unfertilized control (CK), mineral fertilizer (NPK), and three substitution regimes with equal total N inputs: 100% manure (OF), 50% manure + 50% mineral N (MOC), and 25% straw + 25% manure + 50% mineral N (MCS). We quantified soil salinity (total salt content), organic matter and aggregate stability, a multifunctionality-based soil health index, and nematode diversity, trophic composition, co-occurrence networks and assembly (betaNTI; iCAMP). Relative to NPK, organic substitution increased soil organic matter by 33-48% (23.6 to 31.4-34.9 g $kg^{-1}$), improved physical structure (water-stable macroaggregates >0.25 mm: 0.93 to 0.97-0.98; bulk density: 0.94 to 0.81-0.85 g $cm^{-3}$), and reduced soil salinity by 53-62% (0.58 to 0.22-0.27). These habitat improvements increased nematode taxonomic and phylogenetic diversity, reduced plant-parasitic dominance and strengthened food-web complexity (denser, more modular networks). Null-model analyses indicated a shift from stochastic turnover under NPK to stronger heterogeneous selection under organic substitution. Soil multifunctionality increased with nematode taxonomic and phylogenetic diversity and with a higher beneficial-to-plant-parasitic balance, whereas functional richness showed little response. A PLS path model explained 81% of multifunctionality variation and supported a management cascade from improved soil chemical/physical conditions to nematode community restructuring and higher multifunctionality. Together, our results provide management-relevant, indicator-based evidence that partial-to-full organic substitution can reverse secondary salinization and structural degradation in plastic greenhouses without significant loss of crop-support indicators, and that nematode metrics can serve as practical bioindicators for soil health monitoring and optimization of fertilization practices in protected vegetable production.

# Cadmium Uptake by Maize Grown with Microplastics and Their Effect on Water Content and Grain Quality

**ABSTRACT**

Microplastics are a vector for heavy metal uptake into roots and shoots of grain crops. However, it is not known if they increase uptake into the grain. Therefore, the main objective of this experiment was to determine if grain of maize (*Zea mays* L.) had more cadmium (Cd) in it when grown with microplastics in the soil than when grown without microplastics. The microplastic used was polyethylene glycol, a hydrophilic polymer. Hydrophilic polymers have long been used to retain moisture in the soil. However, the soil water status in the presence of hydrophilic microplastics has not been reported. Therefore, a second objective of this experiment was to determine the water content of a root medium with and without polyethylene glycol when maize was grown in it. The effect of microplastics on grain quality is essentially unknown. A third objective was to determine the effect of microplastics on protein in maize grain. Maize was grown for 112 days under greenhouse conditions in pots (22 cm diameter; 20.5 cm height; with drainage holes) that contained a peat-based, commercial potting soil. The microplastic was polyethylene glycol (PEG) with molecular weight of 8000. There were four treatments: control pots watered with tap water; pots watered with 100 µg/mL Cd; pots watered with a 2% PEG solution; and pots watered with a 2% PEG solution plus 100 µg/mL Cd. It was a randomized complete block experiment with four blocks. Pots were irrigated with the same amount of irrigating solution. At harvest, Cd concentration in the grain of maize grown with PEG and Cd in the soil was 1.6 times higher than the Cd concentration in grain of maize grown just with Cd (94.7 and 57.4 µg/g, respectively). At harvest, height (+ standard error) of the plants was as follows: controls: 131.9+4.1 cm; no PEG, Cd: 107.6+2.8 cm; PEG, no Cd: 131.1+3.1 cm; PEG, with Cd: 100.9+3.0 cm. Throughout the experiment, pots with PEG in the soil retained more water than pots without PEG. Average gravimetric soil water content during the experiment was as follows: controls: 355.7+27.2%; no PEG, with Cd: 381.1+25.0%; PEG, no Cd: 532.0+18.5%; PEG, with Cd: 577.7+13.9%. At harvest, the protein in the grain was as follows: controls, 18.98+1.51%; no PEG, with Cd: 20.97+1.04%; PEG, no Cd: 25.39+1.11; PEG, with Cd: 30.30+1.25%. The results showed that PEG increased Cd concentration in the maize grain. Cadmium in the irrigating solution reduced height at harvest by about 30 cm compared to the control plants. The presence of PEG in the root medium increased the gravimetric water content by 1.5 times and protein in the grain by 1.4 times.

# Strategies to reduce cadmium and arsenic accumulation in rice to protect human health

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**ABSTRACT**

Rice is a staple food for about half of the global population, for whom rice is also a major dietary source of the toxic metal cadmium (Cd) and metalloid arsenic (As). Contamination of paddy soils with Cd and As is a common problem in some areas of Asian countries, resulting in elevated dietary exposure to Cd and As and significant health risk for the local residents. It is therefore imperative to develop strategies to limit Cd and As accumulation in rice. Substantial progress has been made in recent years on understanding of the biogeochemistry of As and Cd in paddy soils, providing a basis for controlling their bioavailability in soil, although the opposite biogeochemical behaviours of the two trace metal/metalloid in response to fluctuating redox status make it difficult to reduce the bioavailability of both elements simultaneously. Strategies have also been developed to limit the uptake or translocation of Cd and As by rice through plant breeding or biotechnology, based on recent progress on understanding the molecular mechanisms of their uptake, translocation and detoxification. These progresses and future research needs will be discussed in the presentation.

# Ecological and Human Health Risks of Heavy Metals in Coastal Sediments of Grand Bahama Island

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**ABSTRACT**

This study quantified the concentrations of selected heavy metals, chromium (Cr), manganese (Mn), nickel (Ni), cadmium (Cd), antimony (Sb), lead (Pb), copper (Cu), arsenic (As), and zinc (Zn), in surface sediments collected from two coastal sites on Grand Bahama Island: Dover Sound (DS) and East End (EE). Metal concentrations were determined using inductively coupled plasma–mass spectrometry (ICP-MS). Mean concentrations exceeding sediment quality References values at Dover Sound were observed for Cd (25.64 ± 25.64 mg $kg^{-1}$), Sb (44.92 ± 9.62 mg $kg^{-1}$), and Cu (195.33 ± 67.51 mg $kg^{-1}$), while at East End exceedances were recorded for Cd (442.58 ± 137.06 mg $kg^{-1}$) and Sb (56.62 ± 8.31 mg $kg^{-1}$). The pollution load index (PLI) indicated that sediments at both sites were not polluted overall (PLI < 1). In contrast, the ecological risk index (RI) revealed high ecological risk (RI > 600) at most sampling locations, with the exception of sites D2, D3, and D4, largely driven by elevated Cd and Sb concentrations. Contamination factor analysis showed moderate contamination by Cu (1 ≤ CF < 3) and very high contamination by Cd and Sb (CF > 6), while geo-accumulation index values further suggest anthropogenic enrichment of Cd and Sb (Igeo > 1). Human health risk assessment indicates that As and Cd may pose both non-carcinogenic and carcinogenic risks to adults and children. These results demonstrate that localized metal enrichment in coastal sediments can generate disproportionate ecological and human health risks in small island environments, underscoring the need for continued monitoring of Cd, Sb, Cu, and As to support environmental management and resilience.

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# A seminal paper, 25 years on: enrichment factors cited rather than understood

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Determining whether soils, sediments, or waters are contaminated is a recurring challenge in environmental sciences. A widespread approach is to compare measured concentrations with so-called "natural" background values, often operationalised through pollution indices such as enrichment factors. However, the conceptual weaknesses of these approaches have been clearly identified for decades. In particular, a seminal paper published 25 years ago (Reimann and Caritat, 2000) demonstrated why enrichment factors cannot be used in a straightforward or universal manner, given the heterogeneity of the Earth's crust, natural element fractionation, analytical variability, and the influence of biogeochemical processes.

Despite being widely cited, this work is rarely cited correctly. In many cases, the original cautions and conditions attached to the use of enrichment factors are ignored or misunderstood, and the citation serves primarily as a formal justification for their routine application. As a result, enrichment factors have become a methodological reflex, frequently applied "blindly" and often in combination with several other indices, with little reflection on their scientific meaning or limitations.

This contribution revisits the arguments developed in the original study and examines how they have been subsequently interpreted—or misinterpreted—in the literature. Rather than re-demonstrating the technical limitations of enrichment factors, which are already well established, we focus on how and why a method that was explicitly criticised has nonetheless become standard practice. We argue that this trend reflects a broader issue in environmental research: the progressive loss of conceptual understanding behind commonly used tools, and the transformation of critical References into ritual citations.

By highlighting this disconnect between citation frequency and methodological understanding, we aim to stimulate discussion on good scientific practice, the responsible use of indices in contamination studies, and how the soil science community can better preserve and transmit the conceptual meaning of its analytical tools.

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# Oral Exposure of Arsenic-Contaminated Soils Triggers Hepatic Ferroptosis via Iron Dysregulation and Glutathione Metabolism Disruption: From Bioavailability to Mechanisms

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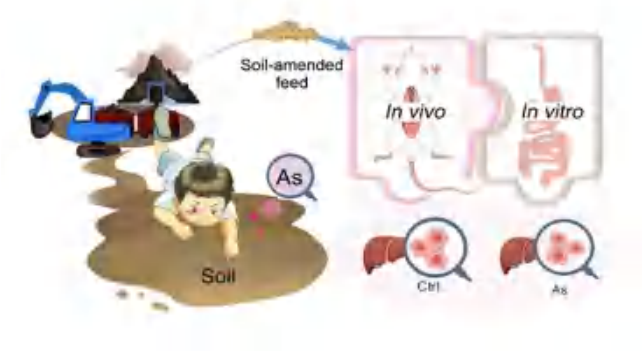
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**ABSTRACT**

Unintentional ingestion of arsenic (As) from contaminated mining and smelting soil poses significant health risks, particularly to liver function. While As-induced hepatotoxicity is documented, the mechanisms linking oral exposure to liver damage remain poorly understood. In this study, we characterized As bioaccessibility through in vitro Solubility Bioaccessibility Research Consortium assays and determined its relative bioavailability using the mouse model. Following 10-day oral exposure, bioaccessibility assays revealed significant variation in As availability. Bioavailable arsenic accumulated in liver tissue, leading to iron overload and oxidative stress. Integrative transcriptomic and metabolomic analyses revealed ferroptosis as the primary mechanism of As-induced programmed cell death in hepatocytes. We discovered that oral As exposure triggers a cascade leading to ferroptosis: disruption of iron homeostasis, impairment of glutathione metabolism, and excessive lipid peroxide production. Mechanistically, As exposure decreased cysteine and glutathione levels while promoting iron accumulation, creating preferred conditions for ferroptotic cell death. These changes were accompanied by altered expression of key iron regulatory genes and disrupted antioxidant pathways, affecting glutathione-dependent defense systems. Our findings establish ferroptosis as critical in As-induced hepatotoxicity and provide insights for risk assessment and therapeutic development. This work advances our understanding of As toxicity mechanisms and offers potential targets for intervention strategies.




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# Particle and mass characteristics influence in vitro and in vivo lead bioavailability from multiple sources

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**ABSTRACT**

Whilst lead (Pb) exposure poses significant risks to human health, understanding its bioavailability (BA) from multiple sources remains challenging. Current human health risk assessments (HHRA) use 250 µm as the upper limit for ingestible particles. In order to achieve a more precise definition for suitable particle sizes, we studied two common lead ores, cerussite and galena, and sieved them into two size fractions: ≤50 µm and 50-250 µm. We then created mixed mineral systems using varying mass ratios (0%, 25%, 50%, 75%, 100%) of these compounds. We used a mouse model to measure the relative bioavailability (RBA) of lead in single and mixed mineral systems in five key tissues: blood, brain, liver, kidney, femur and tibia (bones), after 15 days of oral exposure. Our findings showed that the Pb-RBA across the combined endpoints was 33.1% (95% CI: 27.8%-50.9%) for the ≤50 µm fraction, which was 1.5 times higher than the 50-250 µm fraction (21.5%, 95%CI:18.4%-34.2%). We also assessed in vitro bioaccessibility (IVBA) using four different assays. The SBRC method proved to be the most accurate predictor of lead RBA. The study also presents a new method to estimate the RBA/IVBA of lead mixtures considering both size and mass. We hypothesized and verified that the Pb-RBA of compounds from multiple composite sources is closely related to the Pb-RBA of the single phases they contain and their fraction. The accuracy of this model predictions can reach 79.63%, and the R2 value is 0.64.

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# Green Remediation Theory and Technological Application for Heavy Metal-Polluted Farmland Soils — Chinese Practices and Experience

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## ABSTRACT

Since the beginning of 21st century, soil heavy metal pollution has become increasingly prominent in China, with over-standard rate of polluted farmland sites reaching 19.4%. This poses a grave threat to food security and public health. The green remediation and safe utilization of polluted farmland is not only an urgent environmental challenge to be addressed in China, but also a long-standing research hotspot in the global academic community.

Heavy metal pollution in China's farmland features a wide distribution and high spatial heterogeneity, with slightly, moderately, and heavily polluted plots often coexisting in the same region. This makes it impossible for a single technology to address the issue systematically. Through over 20 years of joint research efforts, this study has broken through a series of key green remediation technologies for heavy metal-polluted farmland, overcome the challenges of low remediation efficiency, short durability, and high costs, and established replicable and promotable safe utilization modes.

1) to address the issues of slightly polluted farmland, which is characterized by large area, wide distribution, and high risk of crop heavy metal content exceeding standards, we originally proposed the concept of "Phytoexclusion" and developed iron-silicon-based soil amendments with multiple barrier functions. When applied in paddy fields, a fourfold barrier system is formed both inside and outside rice plants, including reduced soil metal bioavailability, increased metal absorption at the root surface (via enhanced iron plaque formation), downregulated expression of key genes (*OsNRAMP5*, *OsHMA2*, *OsLCT1*, etc.) involved in root uptake, xylem translocation, and phloem redistribution of heavy metals; and intraplant metal precipitation. Through the application of this iron-silicon-based soil amendment, the average cadmium content in rice grains decreased by 45.4%, arsenic content by 22.5%, and 100% of the rice grains met the national heavy metal standards.

2) to address the moderately polluted farmland where a single barrier technology fails to ensure crops meet safety standards, we identified a batch of heavy metal hyperaccumulator plant resources, and pioneered a high-efficiency heavy metal removal technology centered on "phytoextraction" in China. Based on the interfacial activation effect of phosphorus on arsenic, a phosphorus-based mobilization agent was developed, improving soil arsenic removal efficiency by 39.6%~50.0%. Leveraging the high affinity between cadmium and hydroxyl/amino groups, a chitosan-based carbon mobilization agent was formulated, increasing soil cadmium removal efficiency by 56.1%~116%, thus achieving the goal of reducing heavy metal content in farmland soils.

3) to address the heavily polluted farmland that requires strict regulation, we screened a batch of tolerant cash crops such as *Jatropha curcas*, *Boehmeria nivea* (ramie), and *Sorghum bicolor* (sweet sorghum), developed an alternative cropping - "Phytostabilization" technology based on iron-silicon regulation, and formulated standards including the '*Technical Specifications for Sweet Sorghum Cultivation in Heavy Metal-Contaminated Soils*'. This provides standardized alternative cropping strategies for heavily polluted farmland.

Based on the aforementioned research, this study has innovatively established a "*Phytoexclusion – Phytoextraction - Phytostabilization*" remediation technology system. Listed as key technologies for farmland remediation promotion by the Ministry of Agriculture and Rural Affairs (MARA) and the Ministry of Science and Technology (MOST) of China, this system has been implemented in standardized engineering applications across 23 provinces nationwide, covering a total area of nearly 400,000 hectares. It has continuously provided technical support for the remediation of heavy metal-polluted farmland soils in China.

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# Revisiting Cr Risk in Paddies: Colloidal Cr Formation and Its Mechanistic Impacts on Rice Uptake

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**ABSTRACT**

In studies of heavy metal contamination in rice, traditional frameworks have largely focused on the uptake and toxicity of soluble metal ions, while the colloidal forms widely present under flooded paddy conditions have received far less attention. Trivalent chromium (Cr(III)), in particular, is commonly regarded as a low-toxicity, easily precipitated species and is often underestimated in risk assessments. However, we found that under typical paddy redox conditions, Cr(III) readily forms colloids that exhibit markedly higher mobility and interfacial reactivity than the presumed precipitated form, thereby potentially increasing its entry into the food chain.

This study compared the uptake, translocation, and subcellular distribution of soluble versus colloidal Cr in rice. The results show that inorganic Cr readily transforms into colloids in aqueous environments; these colloids strongly adsorb to root surfaces and act as surface "reservoirs," substantially enhancing Cr accumulation in both roots and shoots. In contrast, strongly chelated soluble Cr remains relatively stable in solution, posing lower exposure to root surfaces and showing markedly reduced uptake and translocation compared with colloidal Cr. Building on this, we further investigated the cellular uptake pathways of Cr colloids of different sizes. Smaller colloids were more prone to enter cells through active uptake processes, whereas larger or more strongly adsorbing colloids were predominantly retained in the cell wall and root-surface microenvironments.

Under realistic agricultural conditions, the colloidal forms of heavy metals should not be overlooked; their formation, stability, and interactions at biological interfaces directly influence plant uptake and ultimately food safety. This work provides a mechanistic perspective essential for recognizing the risks associated with colloidal heavy metals and for guiding contamination management in paddy systems.

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# Mercury sources in soil of forest ecosystems and health risks to birds

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## ABSTRACT

Forests mediate the mercury (Hg) biogeochemical cycling between the atmosphere and terrestrial ecosystems, while there remain substantial knowledge gaps regarding the cycling processes. Here, we determined the mass flow and isotopic compositions/fractionations associated with Hg cycling in the air-water-plant-soil compartments in an evergreen broadleaf forest site in Southwestern China to reveal mechanisms underlying the cycling of Hg. It is found that that annual Hg mass flow is -26.8±12.7 μg $m^{-2}$ $year^{-1}$ for air-foliage $Hg^0$ flux, 6.7±20.5 μg $m^{-2}$ $year^{-1}$ for air-soil $Hg^0$ flux, 9.1±1.2 μg $m^{-2}$ $year^{-1}$ for bulk Hg deposition, 31.8± 10.6 μg $m^{-2}$ $year^{-1}$ for throughfall Hg deposition, 0.3± 0.1 μg $m^{-2}$ $year^{-1}$ for stemflow Hg deposition, and 1.8±0.4 μg $m^{-2}$ $year^{-1}$ for Hg runoff. Mass balance analysis using the flux data shows a 50.4±44.2 μg $m^{-2}$ $year^{-1}$ net atmospheric Hg sink. Interestingly, we observed the $\delta^{202}$Hg shift of 0 to -3.1‰ between air and foliage as leaf age increases, and so for the $\Delta^{199}$Hg shift of 0 to -0.15‰. The observed isotopic composition of foliage Hg and isotopic shift support re-emission of $Hg^0$ occurring after reductive loss from foliage. The $\delta^{202}$Hg shift cause by Hg evasion from soil in summer ranges -0.92‰ to -0.23‰ with a $\Delta^{199}$Hg shift from -0.25‰ to -0.10‰; while in winter only $\delta^{202}$Hg shift is observed with range of -0.28‰ to 0.41‰. Given the isotopic compositions found in soil pore gas ($\delta^{202}$Hg=-0.94±0.32‰, $\Delta^{199}$Hg=-0.49±0.07‰ and $\Delta^{200}$Hg=-0.03±0.04‰) and ambient air ($\delta^{202}$Hg=0.26±0.20‰, $\Delta^{199}$Hg=-0.16±0.06‰ and $\Delta^{200}$Hg=-0.05±0.04‰), legacy Hg re-emission is largely caused by dark reduction processes in deep soil in summer, and by photo-reduction processes in surface soil in winter. Moreover, the distinctly negative $\Delta^{199}$Hg (range of -0.40‰ in Oi to -0.47‰ in Oa) and ~0 $\Delta^{200}$Hg in organic soils indicate atmospheric $Hg^0$ deposition is the dominant source of Hg in soil. Finally, we observed positive $\Delta^{199}$Hg (0.57±0.32‰) and $\Delta^{200}$Hg (0.22±0.06‰) in bulk precipitation, however, the $\Delta^{199}$Hg and $\Delta^{200}$Hg in throughfall (-0.34±0.20‰ and 0.06±0.05‰), stemflow (-0.41±0.20‰ and -0.04±0.08‰) and runoff (-0.40±0.08‰ and -0.02±0.04‰) exhibit distinctly negative values. This suggests a significant atmospheric $Hg^0$ source contribution in throughfall (60±13%), stemflow (96±25%) and runoff (89±23%). Results from mass balance modeling show that atmospheric $Hg^0$ deposition accounts for ~75% of total atmospheric Hg deposition, ~2 times greater than values by the estimate from air-foliage/soil flux. Overall, this study highlights the governing role of atmospheric $Hg^0$ deposition and re-emission processes in Hg cycling of forest ecosystems. Knowledge gaps in mercury (Hg) biomagnification in forest birds, especially in the most species-rich tropical and subtropical forests, limit our understanding of the ecological risks of Hg deposition to forest birds. This study aimed to quantify Hg bioaccumulation and transfer in the food chains of forest birds in a subtropical montane forest using a bird diet recorded by video and stable Hg isotope signals of biological and environmental samples. Results show that inorganic mercury (IHg) does not biomagnify along food chains, whereas methylmercury (MeHg) has trophic magnification factors of 7.4−8.1 for the basal resource− invertebrate−bird food chain. The video observations and MeHg mass balance model suggest that Niltava (Niltava sundara) nestlings ingest 78% of their MeHg from forest floor invertebrates, while Flycatcher (Eumyias thalassinus) nestlings ingest 59% from emergent aquatic invertebrates (which fly onto the canopy) and 40% from canopy invertebrates. The diet of Niltava nestlings contains 40% more MeHg than that of Flycatcher nestlings, resulting in a 60% higher MeHg concentration in their feather. Hg isotopic model shows that atmospheric $Hg^0$ is the main Hg source in the forest bird food chains and contributes >68% in most organisms. However, three categories of canopy invertebrates receive ~ 50% Hg from atmospheric $Hg^{2+}$. Overall, we highlight the ecological risk of MeHg exposure for understory insectivorous birds caused by atmospheric $Hg^0$ deposition and methylation on the forest floor.

# Dietary strategies to reduce bioavailability and toxicity of lead, cadmium, and arsenic following oral exposure: Mechanisms and health implications

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**ABSTRACT**

Currently, the health of the world population faces severe challenges due to exposure to multi-media, multi-pathway, and multi-heavy-metal compound pollution. Traditional heavy metal health prevention strategies have primarily focused on pollution source management. There is an urgent need to reduce intestinal absorption efficiency of heavy metals after ingestion, i.e., bioavailability. In-depth research on the factors influencing heavy metal bioavailability in the human body and its mechanisms of action, as well as the development of technologies to reduce heavy metal bioavailability, can provide innovative scientific solutions for the prevention and control of human heavy metal exposure. In recent years, the speaker has systematically conducted research on dietary regulation mechanisms to mitigate health risks from heavy metal exposure, with a particular focus on nutritional element antagonism and gut microbiota optimization. Firstly, the regulatory effects of calcium and iron supplementation on the expression of intestinal calcium, phosphorus, and iron absorption channels were revealed. A new understanding was established regarding the simultaneous reduction of lead, cadmium, and arsenic intestinal absorption through calcium supplementation. The optimal calcium and iron supplements for protective effects were identified. Additionally, new mechanisms were uncovered, showing how gut microbiota influences the absorption of nutritional elements, participates in the metabolic transformation of heavy metals within the gut, and regulates intestinal barrier functions to control heavy metal bioavailability. Furthermore, differences in cadmium bioavailability between rice and wheat, as well as between indica rice and japonica rice, were revealed. Based on Cd bioavailability differences, a novel dietary structure adjustment technique was established to reduce the risks of cadmium and arsenic exposure. Our research provides a comprehensive foundation for developing innovative approaches to mitigate heavy metal exposure risks through dietary and biological interventions, which are important to protect human health from toxic metal exposure in active manner.

# Agricultural Water Reuse: Effects on Soil and Ecosystem Health

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**ABSTRACT**

The use of reclaimed wastewater for agricultural irrigation is essential for water security in arid regions, yet it presents a challenge by introducing pollutants of emerging concern, specifically pharmaceuticals and personal care products (PPCPs), into the agro-environment. This study leverages Israel, which recycles approximately 90% of its wastewater for agricultural irrigation, as a Living Lab to investigate the fate of PPCPs across the water-soil-plant continuum and their potential for food chain transfer.

Analysis revealed widespread contamination: Reclaimed irrigation water and soils irrigated with this type of water contained tens of different PPCPs. Number of PPCPs and their concentrations strongly correlated with wastewater treatment type and source. Critically, PPCPs were detected in all tested crops (sampled across the country). Leafy greens exhibited the highest number of pollutants of emerging concern at the highest concentrations reaching up to >2000 ng/g. Carbamazepine and venlafaxine (psychoactive pharmaceuticals) exhibited the highest detection frequencies in the fresh produce. The accumulation factor of PPCPs in plant leaves was observed to decrease with increasing soil organic matter content.

The findings of this study, aligning with our publications in this subject, are of importance to human health, providing essential, real-world data that directly addresses the public health risk associated with consuming food irrigated with recycled wastewater. By demonstrating that xenobiotics like Carbamazepine—a compound known for its persistence and recalcitrance to conventional treatment— are successfully taken up by food crops and subsequently excreted in human urine following consumption of the produce, this research provides the necessary "proof of concept" to guide risk assessments. This concrete evidence is vital for the development of unified, health-protective regulations and advanced treatment strategies required to ensure the long-term safety and sustainability of water reuse for food production globally.

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# Harnessing Non-Conventional Salt-Accumulating Plants for Integrated Phytodesalination and Sustainable Salinity Management

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**ABSTRACT**

Soil salinization, driven by geogenic and anthropogenic factors, affects over 830 million hectares globally, severely compromising agricultural productivity, food security, and ecosystem stability. Salinity impedes plant growth via hyperosmotic stress, $Na^+/Cl^-$-induced ionic toxicity, and oxidative damage, particularly in arid, semi-arid, and coastal zones where irrigation and evaporation intensify salt accumulation. Conventional remediation methods (e.g., gypsum amendment, leaching) are often costly, energy-intensive, and ecologically unsustainable. In contrast, biosaline agriculture harnesses salt-tolerant halophytes for phytodesalination, a scalable, eco-friendly strategy that rehabilitates degraded soils while enabling resource-efficient production of food, fodder, bioenergy, and phytochemicals. This ABSTRACT focuses on the genus *Pennisetum* (Poaceae), including *P. glaucum* (pearl millet) and *P. giganteum* (Giant Juncao), as model dual-purpose systems. Though halophytes constitute <1% of terrestrial flora, they deploy sophisticated adaptations: osmotic adjustment via proline and glycine betaine, ion compartmentalization by *SOS1* and *NHX* transporters, and salt excretion through specialized glands. *Pennisetum* species thrive on marginal saline soils, improve soil structure, and yield high biomass for fodder, bioenergy, and biorefineries, while producing bioactive compounds with nutraceutical potential. Their $C_4$ photosynthetic efficiency, rapid growth, and genetic plasticity make them ideal for climate-resilient agriculture. We advocate a multidisciplinary framework integrating agronomy, soil science, and biotechnology to accelerate halophyte domestication, support farmer-centered policies, and apply genomic tools to enhance salinity resilience. This approach can convert saline lands into productive agroecosystems, advancing UN Sustainable Development Goals (SDG 2, 13, 15). Ultimately, redefining salinity from a constraint to a resource heralds a transformative, nature-based paradigm for 21st-century sustainable agriculture.

**Keywords:** Soil salinity; phytodesalination; biosaline agriculture; *Pennisetum* species; sustainable intensification

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# Hyphospheric Phosphorus Enhances Arsenic Hyperaccumulation in Pteris vittata via Coordinated Mycorrhizal and Root Uptake Pathways

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**ABSTRACT**

Arbuscular mycorrhiza fungi (AMF) enhance phosphorus uptake in As-hyperaccumulator *Pteris vittata*, but how hyphospheric P acquisition influences As accumulation remains unclear. We investigated the underlying mechanisms by measuring *P. vittata* growth, AMF colonization, As/P uptake, fatty acid metabolisms, and P transporter expressions. *P. vittata* was grown for 3 months in soil containing 100 mg/kg As with/without AMF, and 50 mg/kg P was applied to the rhizosphere or hyphosphere using a three-compartment rhizobox. Compared to rhizospheric P+AMF treatment, hyphospheric P+AMF increased *P. vittata* biomass by 24%, driven by its 22% greater AMF colonization. The increased colonization resulted from 1.4-fold greater fatty acid content to supply AMF with essential carbon, consistent with 2-fold greater expression of fatty acid synthesis (*PvFatM*) and lipid transport (*PvSTR*) genes. Hyphospheric P also activated two complementary P-transport pathways via upregulating expressions of plant *PvPht1;6* and AFM *RiPho84* and *RiPT7* by 1.8−2.2 fold for mycorrhizal uptake, and plant *PvPht1;3* by 2.5-fold for root uptake. Together, these processes elevated the frond As content in *P. vittata* by 29% to 9119 mg/kg. Our findings reveal that AMF-facilitated P uptake drives As hyperaccumulation through coordinated mycorrhizal and root uptake pathways, providing a mechanistic basis for optimizing phytoremediation in contaminated soil.

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# Arsenic-hyperaccumulator Pteris vittata effectively uses sparingly-soluble phosphate rock: Rhizosphere solubilization, nutrient improvement, and As accumulation

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## ABSTRACT

Sparingly-soluble phosphate rock (PR), a raw material for P-fertilizer production, can be effectively utilized by the As-hyperaccumulator *Pteris vittata* but not terrestrial plants in most cases. In this study, we investigated the associated mechanisms by measuring organic acid exudation and acid phosphatase in the rhizosphere, and nutrient uptake and gene expression related to the As metabolism in *P. vittata.* The plants were grown in a soil containing 200 mg $kg^{-1}$ As and/or 1.5% PR for 30 days. Compared to the As treatment, the *P. vittata* biomass was increased by 33% to 4.6 g $plant^{-1}$ in the As+PR treatment, corresponding to 27% decrease in its frond oxidative stress as measured by malondialdehyde. Due to the PR-enhanced dissolved organic carbon (DOC) production in the rhizosphere, the Ca, P, and As contents in *P. vittata* fronds were increased by 17% to 9.7 g $kg^{-1}$, 29% to 5.0 g $kg^{-1}$, and 57% to 1045 mg $kg^{-1}$ in the As+PR treatment, thereby supporting its better growth. Besides, PR-induced rhizosphere pH increase from 5.0 to 6.9 promoted greater P uptake by *P. vittata* probably via upregulating low-affinity P transporters *PvPTB1;1/1;2* by 3.7−4.1 folds. Consequently, 29% lower available-P induced the 3.3-fold upregulation of high-affinity P transporter *PvPht1;3* in the As+PR treatment, which was probably responsible for the 58% decrease in available-As content in the rhizosphere. Consistent with the enhanced As translocation and sequestration, arsenite antiporters *PvACR3/3;3* were upregulated by 1.8−4.4 folds in the As+PR than As treatment. In short, sparingly-soluble PR enhanced the Ca, P, and As availability in *P. vittata* rhizosphere and improved their uptake via upregulating genes related to As metabolism, suggesting its potential application for improving phytoremediation in As-contaminated soils.

**Keywords:** Ca and P uptake, DOC and phosphatase, high-affinity P transporters *PvPht1;3/1;4*, low-affinity P transporters *PvPTB1;1/1;2*, arsenite antiporters *PvACR3/3;1−3;3*

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# Luxury at a Cost: Linking Portable XRF-Based Bioaccessible Chromium to ICP-MS-Determined Chromate and Dermal Permeation Risk in Bright-colored Leather Products

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## ABSTRACT

The extensive use of chromium (Cr) in leather tanning creates a potential dermal exposure risk to consumers from toxic chromate (CrVI) in finished leather products. Here, we combined a large-scale market survey and permeability-based health risk assessment. First, we analyzed 470 commercial genuine leather products from 7 countries using a calibrated portable X-ray fluorescence spectrometer (pXRF). Measurements revealed exceptionally high total Cr, with 93% of samples exceeding 10,000 mg $kg^{-1}$, highest being 60,200 mg $kg^{-1}$. A positive correlation was found between product price and total Cr content ($R^2$=0.65), indicating higher levels in luxury full-grain leathers. To assess the bioavailable risk, we quantified bioaccessible Cr in artificial sweat extracts using pXRF (474–4,460 mg $kg^{-1}$), achieving excellent agreement with ICP-OES data ($R^2$=0.992). Critically, this bioaccessible Cr pool showed a strong correlation ($R^2$=0.77) with CrVI content determined by ICP-MS ranged from 0.33 to 141 mg $kg^{-1}$, with 86% of samples exceeding the European Union limit of 3 mg CrVI $kg^{-1}$. Specifically, color-based analyses suggest that brighter-colored leathers exhibited higher bioaccessible Cr and CrVI contents. Moreover, 5 leather samples with the highest bioaccessible Cr were further assessed for Cr permeation through mouse skin by Franz diffusion cells, indicating a positive correlation between permeable Cr and CrVI concentration in simulated sweat solution, which were utilized to refine exposure for human health risk assessment. Long-term dermal exposure to Cr in leather products may pose both permeable-Cr induced non-carcinogenic and permeable-CrVI induced carcinogenic risk for adults and children. This study demonstrates that pXRF can be transformed into a validated tool for rapid, risk-based screening, providing a method to monitor and mitigate Cr exposure from the global leather consumer market, highlighting bright-colored luxury leather products may pose carcinogenic risk via dermal contact, emphasizing the need for increased attention to potential Cr exposure from leather products.

**Keywords**

Portable X-ray fluorescence spectrometer; full-grain leather by Cr tanning; Cr bioaccessibility and speciation; Franz diffusion cell with mouse skin; permeable-chromate induced carcinogenic risk.

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# Soil health mediates diversification effects on crop resilience in tropical agroecosystems

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**ABSTRACT**

The increasing frequency of extreme climate events threatens agricultural production and food security, especially in tropical regions. Climate adaptation management solutions that enhance soil health are key strategies to ensure production stability and improve the resilience of agricultural systems. Understanding how soil processes interact to support ecosystem functioning is essential for elucidating the pathways through which management influences yield. Here we reveal how sustainable management practices that increase agroecosystem diversification influence the functional networks that underpin soil health, resilience and stabilize yields in a region highly exposed to climate variability. Thirteen farmer-led experiments under contrasting management were assessed through topsoil (0–10 cm) sampling. Twelve chemical, physical, and biological soil health indicators were integrated through Exploratory Factor Analysis to derive latent soil function constructs. A Structural Equation Modeling framework quantified how diversification influences crop yield and crop instability through soil-health-mediated pathways. The soil indicators explained 79% of soil health variance, while crop yield was explained at 64% by the model. Soil health emerged as the primary mediator linking diversification to crop yield, acting through direct effects and four indirect pathways: (i) complex pore networks formed by diverse root systems provided physical support for plant growth and enhanced carbon dynamics and storage; (ii) improved physical structure promoted greater soil water storage; (iii) nutrient balance and microbial functioning enhanced the biochemical regulation of soil processes; and (iv) diversification directly increased soil water retention, jointly sustaining higher yields. Maintaining soil cover in diversified systems created a protective buffer against degradation driven by extreme climatic events. Crucially, healthier soils reduced crop instability by improving water retention and buffering crops against climatic fluctuations. Crop instability exerted strong negative effects on yield, demonstrating that resilience is strongly shaped by soil health mediated responses. Integrated diversification strategies led to yields up to 2.5 times higher than the state average, emphasizing that soil health is a critical mechanism through which diversified tropical agroecosystems achieve greater stability and predictability under climate stress. Strengthening soil multifunctionality through diversified management offers a solution that integrates both adaptation and mitigation, contributing to climate resilience and long-term food security in vulnerable tropical agricultural regions.

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# Multi-dimensional Drivers for Urban Soil Microbial Diversity: Insights from the Species-area Relationship

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**ABSTRACT**

In light of rapid urbanisation globally, urban expansion is creating pressure on soil ecosystem services, threatening their ecological functions. The soil microbial community is essential for sustaining soil health and ecosystems, yet its distribution patterns and driving mechanisms within highly heterogeneous, fragmented urban environments remain unclear. This study focuses on five types of urban parks in Ningbo (Zhejiang, China). The research aims to (1) test the applicability of the classical species-area relationship (SAR) to soil microbial communities in urban parks; (2) elucidate how soil environmental factors mediate the relationship between park area and microbial community; (3) identify the key socio-economic and climatic factors that interact with natural variables to indirectly shape microbial community; (4) examine the habitat heterogeneity hypothesis as a potential mechanistic explanation for the observed SAR; and (5) clarify the synergistic regulatory mechanisms of natural and anthropogenic factors on the multifunctionality and service sustainability of urban park soils. By the application of environmental DNA (eDNA) technology, we construct a drivers-functions-management analytical framework in this study. The findings are expected to provide empirical scientific support for ecology-based urban soil conservation and resilience management.

**KEY WORDS:** Urban Parks, Soil Microbial Diversity, Environmental DNA, Species-area Relationship, Multi-dimensional Drivers

# Health risk assessment of dietary cadmium exposure based on cadmium bioavailability in food: opportunities and challenges

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**ABSTRACT**

Long-term exposure to cadmium (Cd) through contaminated food can lead to multiple adverse health effects. Although previous studies have addressed global food Cd concentrations and dietary Cd exposures across different populations, there are increasing concerns regarding the adequacy of current food Cd safety standards to protect populations from adverse health effects. Moreover, food Cd relative bioavailability (Cd-RBA) has been shown to improve the accuracy of health risk assessment, however, factors influencing food Cd-RBA have not been systematically discussed, hindering its application in risk assessment. This review aims to provide an overview of Cd contents in food, discuss concerns regarding international food Cd concentration standards, explore factors influencing food Cd bioavailability, and highlight the opportunities and challenges in refining differences between dietary Cd intakes and body burdens. Our findings suggest that current safety standards may be insufficient to protect human health, as they primarily focus on kidney damage as the protective endpoint and fail to account for global and regional variations in food consumption patterns and temporal changes in dietary habits over time. Factors such as crop cultivars and food compositions greatly influence food Cd-RBA. To improve the accuracy of Cd health risk assessment, future studies should incorporate food Cd-RBA, sociodemographic characteristics, nutritional status, and incidental Cd exposure. This review highlights new insights into food Cd safety standards and Cd bioavailability, identifies critical knowledge gaps, and offers recommendations for refining health risk assessments. This information is essential in informing future bioavailability investigations, health risk assessment, and safety standard development.

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# How Does Vegetation Cover Alter Mercury Accumulation and Mobility in Soils of Guizhou?

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**ABSTRACT**

Mercury (Hg) is a global pollutant. As the core area of the southwest karst region in China, Guizhou faces prominent soil Hg pollution risks due to the combined effects of high Hg geological background and anthropogenic activities. Since 1990, the forest coverage rate in Guizhou has increased significantly from 14.8% to 63.3%. Changes in vegetation cover may regulate the adsorption, migration, and speciation transformation processes of soil Hg. Taking a typical karst area in Guizhou as the research object, this study systematically revealed the impact of vegetation cover change on soil Hg fractionation and migration by integrating field sampling data of 470 topsoil samples, remote sensing NDVI data, climate factors, and land use information, Correlation analysis, principal component analysis (PCA), and structural equation modeling (SEM) were used to systematically reveal the effects of vegetation cover change on soil Hg speciation differentiation and migration.. The results showed that the total soil Hg (THg) content in the study area presented a distribution characteristic of cropland > rice paddy> forestland > grassland, while the proportion of Dissolved Hg (DHg) was the highest in forestland (0.133 ng $g^{-1}$). Significant differences in Hg distribution patterns were observed between karst and non-karst areas. Vegetation significantly enhanced soil Hg retention through litter accumulation and root adsorption. This study clarified the driving mechanism of vegetation cover on soil Hg fractionation and migration, identified the key points of Hg pollution prevention and control for different vegetation types, provided a new perspective for in-depth understanding of the soil Hg cycling process under special geological backgrounds, and offered scientific basis for regional Hg pollution risk management and ecological restoration.

# Calcium in Soil Health: Beyond pH Management to Mitigating Phosphorus Overuse and Enhancing Carbon Stabilization

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**ABSTRACT**

Calcium (Ca) is a fundamental regulator of soil health, yet its management in agriculture remains narrowly focused on pH correction, overlooking critical ecological and physiological consequences. This synthesis argues for an optimal, rather than maximal, Ca strategy in agroecosystems based on three interconnected lines of evidence. First, while Ca is essential for soil structure and plant function, excessive Ca can induce stomatal closure and disrupt plant water relations, impairing photosynthesis and resilience under stress. Second, we present a paradigm-shifting perspective on global phosphorus (P) overuse: historical and ongoing misapplication of P fertilizers—particularly in the form of calcium phosphates (e.g., SSP, TSP)—and routine liming have inadvertently driven a hidden over-application of P to meet perceived crop needs of Ca. This has exacerbated soil P accumulation, eutrophication risks, and inefficient use of finite P reserves. Third, Ca plays a vital but underutilized role in soil organic carbon (SOC) stabilization through the formation of Ca-organic complexes, aggregation, and protection of organic matter against microbial decomposition. Re-framing Ca management toward optimal levels could thus simultaneously reduce P pollution, enhance C sequestration, and support plant physiological health. We call for integrated soil–plant Ca diagnostics, Ca-aware P fertilizer recommendations, and a precise nutrient management strategy that leverages Ca's dual role in nutrient stewardship and climate-smart soil systems to achieve sustainable development goals on food security, water quality, and climate action.

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# Biochar laced with elemental sulfur restores microbial function in aridland soils

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**ABSTRACT**

Degraded arid soils often exhibit low microbial activity and impaired nutrient cycling, limiting their capacity to sustain ecosystem functions. This study evaluated the individual and combined effects of biochar (B), and elemental sulfur (S) on soil microbial abundance, enzyme activities, functional gene profiles, taxonomic diversity, and functional diversity related to carbon (C), nitrogen (N), and sulfur (S) cycling. After two months of amendment application, microbial enumeration, enzyme assays, qPCR, high-throughput sequencing (16S rRNA and ITS), functional annotation (FAPROTAX), and multivariate analyses were integrated to assess soil biological responses. Biochar treatments significantly increased bacterial, fungal, and actinomycete abundance, reflecting improved habitat structure, organic substrate availability, and nutrient supply. Biochar reduced the microbial metabolic quotient ($qCO_2$), indicating enhanced microbial carbon use efficiency, whereas sulfur increased $qCO_2$, likely due to shifts toward sulfur-oxidizing communities and altered carbon availability. Sulfur inhibited urease activity when applied alone or with other amendments, consistent with its acidifying and urease-inhibitory role. The combined S+B treatment produced the highest urease activity and balanced enhancement of multiple enzymes, indicating synergistic effects on soil biochemical functioning. qPCR analyses revealed that biochar strongly upregulated carbon degradation genes (e.g., alkane and aromatic hydrocarbon monooxygenases), while suppressing some nitrogen fixation genes. Compost combined with biochar enhanced both C- and N-cycle genes, confirming improved nutrient availability and microbial stimulation. Sulfur addition promoted genes associated with nitrification, denitrification, and sulfur transformation, highlighting its role in driving redox-sensitive pathways. Sulfur promoted functional redundancy within C–N–S cycling but lowered diversity indices due to dominance of specialized guilds. Overall, the combined application of biochar and sulfur most effectively enhanced microbial abundance, functional breadth, and coupled C–N–S cycling. These findings demonstrate that co-amendment strategies optimize soil biological function and resilience in degraded arid soils, supporting sustainable soil management and nutrient cycling. Keywords: biochar; sulfur; amendment; Aridland

# Variation in Arsenic Accumulation and Remediation Potential among Different Genotypes of Pteris vittata

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**ABSTRACT**

Arsenic (As), a widespread toxic metalloid, poses a serious threat to food safety and human health through soil contamination. Phytoremediation, especially using hyperaccumulators, offers an environmentally friendly and cost effective approach for As-contaminated soil. Pteris vittata is the first discovered As hyperaccumulator, exhibiting strong As tolerance and accumulation capacity. It is widely distributed worldwide, and adaptation to different environments has led to diverse populations. Previous studies show significant differences in morphology, genetic makeup, and As accumulation among different populations of P. vittata.

To clarify the differences in As accumulation among genotypes and to identify optimal materials for remediation, this study collected large scale samples from 53 sites across China and introduced three foreign genotypes as an outgroup for calibration. Phylogenetic trees were constructed using chloroplast genome sequences. Morphological traits such as plant height, frond number, leaf shape index, and pinna density were measured. Under greenhouse conditions, spore germination, uniform cultivation, and As treatment experiments were conducted to compare biomass, shoot As concentration, and total As accumulation among populations. Finally, four ecotypes (JS NJ2, GZ ZY, US F3, GX GL1) showing outstanding performance in long term low As soil culture were selected for a two year field remediation evaluation in As-contaminated farmland.

Results showed that based on chloroplast genome evolution analysis, Chinese P. vittata genotypes formed three distinct clusters, indicating differentiated populations. Morphological traits varied significantly among regional types. Under greenhouse conditions, biomass, shoot As concentration, and total As accumulation differed by up to 15.9-, 3.6-, and 23.6 fold, respectively, among genotypes. Analysis of element correlations and expression of key As accumulation genes suggested that the differences in As accumulation may be related to As uptake mediated by Pht1 genes. Five genotypes with high per plant As accumulation and one commonly used remediation genotype were tested in As-contaminated soil. Significant differences in As accumulation capacity were observed, with the ecotype JS-NJ2 performing best, showing a 2-fold improvement compared to the currently used remediation genotype. JS-NJ2 is thus proposed as a suitable material for As-contaminated soil remediation.

This study systematically compared differences in morphology, phylogeny, and As accumulation traits among P. vittata genotypes, revealed potential molecular mechanisms underlying As accumulation, and identified superior ecotypes for field remediation. The findings provide both theoretical support and practical materials for enhancing the efficiency of phytoremediation in As-contaminated soils.

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# Sustainability of mountainous olive orchards: evaluation of soil microbial diversity and functionality of organic, integrated and conventional agroecosystems.

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**ABSTRACT**

There are approximately 4.3Mha of olive trees (*Olea europaea* L.) in the EU, with most of this area located in Spain (50%), Italy (27%) and Greece (16%). Conventional tillage, fertilization and phytosanitary practices are the most widespread management systems in many of these olive-growing regions. The intensification of cultivation is widely recognized as one of the most significant human induced alterations to the global environment. Concerned by these issues, the European Commission has initiated agro-ecological policies promoting environmental-friendly practices. In this context, the interest is being focused on crop production systems, such as organic and integrated agriculture, that optimize yields while preserving soil quality and protecting the environment.

The aim of this study was to evaluate the effect of different olive farming management systems (conventional, integrated and organic) on soil microbial community structure and functional diversity. To obtain a wider perspective of soil health under the different farming systems, these soils were compared them with those from natural ecosystems (Mediterranean forest-shrubland).

The study was conducted at three different locations representative of mountainous olive orchards of South-Eastern Spain. Microbial functional diversity was assessed using MicroResp™ system, a whole-soil method based on community level physiological profiles (CLPP) obtained by testing the utilizations of different carbon sources. In addition, microbial community structure was evaluated analyzing soil ester linked fatty acid profiles (ELFA).

Substrate utilization profiles did not show significant differences among different management systems when analyzed overall. However, these differences were pronounced when management systems were compared within individual study areas.

Significant differences in microbial community structure (ELFA) were observed among different study areas. In contrast, differences in soil microbial communities among agricultural management systems were less pronounced. Nevertheless, a gradual shift in microbial composition was observed from conventional agricultural systems to ecosystems with natural vegetation. This shift was associated with a decrease in fungi markers and monosaturated fatty acids and an increase of fatty acids with hydroxyl group.

Both microbial approaches, particularly ELFA analysis, proved to be good indicators of soil health and were sufficiently sensitive to detect changes in soil quality resulting from olive management systems when compared with natural vegetation ecosystems. However, although different olive management systems (organic, integrated and conventional) showed significant differences in terms of soil microbial community structure (ELFA), they did not differ markedly in terms of functionality (CLPP), suggesting certain functional redundancy of soil microbial communities of these agro-ecosystems.

# Seeing is believing: Exploring metal interactions in rice paddies using chemical imaging tools

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**ABSTRACT**

Understanding the interactions between cadmium (Cd), manganese (Mn), and selenium (Se) is crucial for managing their bioavailability in rice paddies. This study integrates findings from multiple field and rhizotron experiments, employing a suite of *in situ* chemical imaging tools, including diffusive gradients in thin-films (DGT), planar optodes (PO), and soil zymography, to visualize and quantify these dynamics. High-resolution DGT imaging revealed spatially heterogeneous, inversely correlated fluxes of labile Cd and Mn in the rhizosphere. The application of Mn oxides ($MnO_2$ and $Mn_2O_3$) significantly reduced Cd bioavailability (by up to 28.9%) and uptake in rice. This remediation effect was mechanistically explained by the DGT-induced fluxes in soils (DIFS) model, which showed that Mn addition prolonged the soil solid-phase response time ($T_c$) and slowed the Cd desorption rate ($k_{-1}$). In naturally enriched soils, DGT measurements further identified a critical labile Se:Cd molar ratio; values below 0.7 indicated Cd risk, whereas ratios increasing from 0.7 to 20 progressively lowered grain Cd concentration. The integrated chemical imaging platform consistently outperformed traditional extractions in predicting grain metal uptake. This work demonstrates that direct visualization via chemical imaging, coupled with kinetic modeling, provides unparalleled insight into metal interactions. It offers a powerful approach for developing targeted strategies to mitigate Cd contamination and leverage beneficial Se and Mn interactions for safer rice production in contaminated or geogenically enriched paddies.

**Acknowledgments**

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# Heavy metals migration from soil to animal/human in heavy metal contaminated areas: Fate and risk of legacy Pb and Cd

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## ABSTRACT

Nonferrous metal smelting is one of the predominant sources of heavy metal accumulation in the environment. China is the world's largest producer and consumer of several highly toxic heavy metals. Over the past three decades, the production of Pb, Cd, and Zn in China has undergone three major phases: a rapid growth phase characterized by weak pollution control, a slowdown phase, and a rejuvenation phase. The shutdown of many small-scale smelters between 2005 and 2012 substantially reduced heavy metal emissions from smelting activities; however, large amounts of legacy heavy metals accumulated in soils, dust, and sediments at smelting sites still require proper management. Measures such as relocating residents from contaminated areas to clean areas and converting polluted farmland to forest are among the most effective approaches for reducing human exposure to heavy metals. There is also evidence that heavy metal concentrations in local ground dust have steadily declined over the past decade. Another important source of Cd pollution is Cd battery manufacturing, which has caused severe Cd accumulation in soils and wheat grains in Xinxiang, China.

Soil is the primary sink for heavy metals emitted from industrial activities. After contaminated farmland is no longer used for crop cultivation, the transfer of heavy metals to humans through crops is greatly reduced; however, the migration of pre-existing heavy metals in soil to higher trophic levels of the food chain still occurs, a process that remains insufficiently studied. In this study, the transfer of soil heavy metals was investigated in both a soil–native plant–woodlouse system and a soil–free-range chicken system.

In the soil–plant–woodlouse system near a long-term nonferrous metal smelter, paired soil samples (total Cd: 1.15–34.5 mg/kg; total Pb: 36.7–1090 mg/kg), native plants (Humulus scandens, Digitaria sanguinalis and Setaria viridis), and woodlice (Armadillidium vulgare) were collected and analyzed to assess heavy metal transfer. The native plants exhibited higher bioconcentration factors (BCFs) for soil Cd, Cu, and Zn than for Mn, Ni, and Pb, although all BCF values were <1.0. Mean concentrations of Cd, Cu, Mn, Ni, Pb, and Zn in woodlice were 20.5, 697, 169, 5.41, 472, and 424 mg/kg, respectively. The BCFs of woodlice indicated much greater accumulation of Cu, Cd, and Zn than of other metals, suggesting an elevated health risk for woodlouse predators. Mean woodlouse BCFs for plant Cd, Cu, and Zn were 11.2, 52.6, and 10.6, respectively. For samples collected at increasing distances from the smelter, a declining trend in woodlouse Cd concentrations was observed, whereas no such trend was evident for Pb. In addition, the bioaccumulation factors of Cd and Pb in woodlice from plants and soil exhibited a nonlinear decrease with increasing heavy metal concentrations in soil or plants.

In the soil–free-range chicken system, samples of free-range chicken organs (liver, kidney, heart, intestine, and gizzard) were collected from areas affected by nonferrous metal smelting, Cd battery production, and from areas free of heavy metal contamination. The results showed that free-range chickens raised near the nonferrous metal smelter and in the Cd battery production area contained substantially elevated Cd concentrations in their organs. In the Cd battery production area, mean Cd concentrations followed the order: liver (8.33) > gizzard (4.66) > kidney (1.80) > intestine (1.45) > heart (0.390 mg/kg, dw). In the nonferrous metal smelting area, the sequence was liver (5.11) > intestine (2.23) > gizzard (1.75) > kidney (0.650) > heart (0.123 mg/kg). In contrast, Cd concentrations in market chicken samples were all <0.1 mg/kg, ranging from 0.0102 to 0.0877 mg/kg. In areas free from heavy metal contamination, organ Cd concentrations of free-range chickens ranked as intestine (0.130) > gizzard (0.0900) > liver (0.0763) > kidney (0.0235) > heart (0.0151 mg/kg). In the nonferrous metal smelting area, Pb concentrations in free-range chicken organs followed the order: intestine (1.73) > liver (1.29) > gizzard (0.849) > kidney (0.743) > heart (0.300 mg/kg).

Comparisons among different chicken samples indicate that: (i) in nonferrous metal smelting areas and Cd battery production areas, there is a significantly increased risk of Cd exposure to consumers through the consumption of free-range chicken organs, and free-range chicken farming should be prohibited in such contaminated areas; (ii) in nonferrous metal smelting areas, similar risks also exist for Pb exposure; and (iii) compared with Chinese food quality standards, market chickens and free-range chickens from non-polluted areas contain Pb and Cd at safe levels.

Overall, these results highlight the persistent risks posed by legacy heavy metals in contaminated soils. Strict control of land use and careful consideration of heavy metal transfer from soil to the food chain are essential in polluted areas.

**Keywords:** heavy metal; soil; food chain; woodlouse; free-range chicken; liver

# Divergent Responses of Topsoil and Subsoil Microbial Communities to Cadmium Stress in a Wastewater-Irrigated Farmland

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## ABSTRACT

Microbial communities are pivotal to soil and environmental health, ecological functions and agricultural productivity. However, microbial community responses to soil cadmium (Cd) contamination remain unclear. Therefore, we comprehensively analyzed bacterial and fungal diversity, composition and community stability in both topsoil (0–20 cm) and subsoil (20–40 cm) from a long-term wastewater-irrigated farmland on the North China Plain, under low (mean Cd = 0.53 mg/kg), medium (1.23 mg/kg), and high (2.64 mg/kg) Cd levels. Results showed that topsoil fungal Hill-α diversity decreased significantly with rising Cd levels. Differentially abundant operational taxonomic units (OTUs) across Cd levels were mainly affiliated with bacterial Phyla Acidobacteriota, Actinobacteriota, Bacteroidota and Chloroflexi, and fungal Phyla Ascomycota, Basidiomycota, Chytridiomycota and Mortierellomycota, respectively. Only 1%–10% of OTUs exhibited monotonic changes in relative abundance with increasing Cd contents. Cd levels significantly altered microbial community structures (β-diversity), explaining 34.1%–63.7% of bacterial and 55.2%–70.9% of fungal compositional variation in topsoil, and 12.0% (bacteria) and 18.5% (fungi) in subsoil. Based on LefSe analysis (LDA score ≥2) and abundance monotonicity, 45 bacterial and 21 fungal Cd-indicating biomarkers were identified, belonging to bacterial Orders Burkholderiales, Gemmatimonadales, Thermomicrobiales, and fungal Families Mortierellaceae and unclassified, respectively.

Co-occurrence network analysis revealed that Cd exposure increased average degrees but reduced modularities of microbial networks (except for topsoil fungi), indicating enhanced interspecific interactions but weakened community stabilities, with subsoil bacterial communities being the most vulnerable. Bacteria-fungi linkage densities at the phylum level increased with Cd levels, confirming strengthened cross-kingdom interactions under Cd stress. A polarization effect was observed: network nodes shifted from uniform multi-module distribution to aggregation into fewer modules as Cd levels increased, suggesting microorganisms tended to form fewer but more robust assemblages under Cd stress. Distinctively, modularity of the topsoil fungal network increased with Cd levels, reflecting strong resistance to environmental disturbances.

In conclusion, compared to bacteria, topsoil fungi were able to maintain community stability and ecological functions via compositional regulation under Cd stress. Our study highlights the vulnerability of subsoil bacterial communities and the potential application of topsoil fungal microbiota in the bioremediation of Cd-contaminated soils.

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# From Predict to Control Cr(VI) Risk in Agricultural Soil: Aging Model and S-nZVI Stabilization for Crop Safety

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**ABSTRACT**

Prediction and controlling hexavalent chromium (Cr(VI)) contamination in agricultural soils are crucial for crop safety and sustainable production. Here, eight agricultural soils spiked with 20-300 mg $kg^{-1}$ Cr(VI) were aging for 180 d to develop an aging model to predict Cr(VI) transformation. Then sulfidated nanoscale zero-valent iron (S-nZVI) was tested to immobilize residual Cr(VI) in two contrasting soils by evaluating Cr speciation, leachability and wheat phytotoxicity. Results showed that higher pollution level accelerated early-stage reduction kinetics, but also increased the bioavailable Cr(VI) fraction and reduced the overall reduction efficiency, which was more pronounced in alkaline soils. This highlights scenarios where natural attenuation is unlikely to eliminate Cr(VI) rapidly. Kinetic modeling indicated a predominantly chemisorption-associated reduction process, while diffusion-limited mechanisms became increasingly important at higher loadings, providing a mechanistic framework for scaling transformations across concentration gradients. A multiple linear regression model incorporating pollution level, aging time, pH, and organic matter significantly improved the prediction of Cr(VI) reduction ($R^2$= 0.74). Guided by these high-risk scenarios, sulfidated nanoscale zero-valent iron (S-nZVI) was evaluated to immobilize Cr(VI) in two contrasting soils with comparable Cr(VI) concentration. At an optimal S/Fe molar ratio of 0.1, S-nZVI achieved dose-dependent immobilization (>93% reduction at 10 g $kg^{-1}$ within 28 days), shifted Cr from labile to more stable fractions, and significantly reduced leachable and plant-available pools, being consistent with Fe(III)–Cr(III) co-precipitation as confirmed by XRD, SEM-EDS, and XPS analyses. Wheat growth assays further revealed a soil-specific safe-dosing window: moderate S-nZVI amendments alleviated Cr phytotoxicity, whereas excessive application induced Fe-related stress and inhibited growth. Our study provide a model to predict Cr(VI) redox transformation and highlight soil-specific management of Cr(VI) when employing engineer material as amendment.

# PFAS in Agro-Food Systems: Risk Management Strategies

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**ABSTRACT**

Per- and polyfluorinated substances (PFAS) encompasses thousands of compounds with diverse structures. Their extremely low safety thresholds make them an urgent concern in agricultural-food systems. PFAS may enter agricultural fields from point sources such as industrial activities, and non-point sources from the use of biosolids for fertilization, and wastewater and other contaminated water sources for irrigation. Due to the large numbers of PFAS, a wide range of scenarios in the source and nature of PFAS contamination, and the vast area and complexity of agro-food systems, it is a formidable task to manage potential PFAS risks in agro-food systems. A first-step strategy is to prioritize the types of PFAS, crop species and agronomic practices that may present the greatest risk for PFAS contamination of food produce. This may be achieved by understanding PFAS uptake, translocation and accumulation as a function of PFAS structures as well as plant species. Existing knowledge from other contaminants, including pesticides, may be leveraged and incorporated into data-driven models to predict and identify a short list of "high risk" scenarios. Resources can then be focused on developing management practices to ensure minimal transfer of PFAS into food produce for these high-risk scenarios. For the majority of scenarios, however, PFAS likely pose only a low to moderate risk in the context of food contamination. For the moderate risk scenarios, risk avoidance may be a practical yet effective strategy to ensuring safety. An example is the use of biosolids in agricultural fields. Some PFAS are likely enriched in biosolids, especially when there are contributions of industry sources to the waste stream. In such cases, biosolids may be isolated to applications after harvest or before planting, and uses on non-food crops such as cotton and trees, feed crops, or fruiting plants that have biological barriers to deter contaminant translocation to edible organs. Such risk-avoidance strategies are low-cost and easily implementable and can be particularly practical for addressing PFAS concerns in agro-food systems.

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# Phosphorus and cover crop management practices alter phosphorus speciation in soils and eroded sediments

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## ABSTRACT

Agricultural runoff often contributes to phosphorus losses in dissolved and sediment-bound forms, impacting water quality. No-till and cover cropping practices are effective strategies that crop managers can implement to reduce erosion and nutrient loss. The overall aims of this long term study were to characterize and evaluate the effects of fertilizer (placement and source) and cover crop management on P speciation in source soil and surface runoff sediments. In 2014, a field-scale experiment was established in a no-till, corn (Zea mays L.)-soybean (Glycine max L.) cropping system with two cover crop treatments (with and without a winter crop; cereal rye (Secale cereale L.)) and three P fertilizer management treatments (2014- 2020, no P, fall broadcast diammonium phosphate, and spring subsurface injected ammonium polyphosphate and 2020-2023 no P, drawdown, and build and maintenance via subsurface injected APP). Phosphorus fractionation in source soil collected in the fall of 2019-2022 and sediment samples collected throughout 2020-2023 were analyzed using a modified sequential P extraction method to evaluate the cumulative effects of imposing the treatment factors over the first five years (2014-2019) and annually after 2020. The direct P speciation was performed using X-ray absorption near edge structure spectroscopy. Findings showed that P management and cover cropping significantly influenced P fractions and speciation in both soils and sediments. Further, sediments collected later in the study (after 2020) showed a greater effect of cover crop management on additional sediment P fractions. Runoff sediments were generally enriched in P relative to the source soils, likely due to increased organic matter and stimulated root and microbial activity, which affected P stabilization through sorption, precipitation, and occlusion within aggregates. These results demonstrate that integrated P fertilizer and cover crop management influence P speciation and mobilization in soils and sediments, providing insight for nutrient management and erosion mitigation in long-term no-till systems. Developing P fertilizer and cropping system management options, with an understanding of soil P transformations, helps maintain environmental sustainability.

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**Keywords**

Agricultural management practices, Source soil, Runoff Sediment, P fractionation, P speciation

# Recruitment of copiotrophic and autotrophic bacteria by hyperaccumulators enhances nutrient cycling to reclaim degraded soils at abandoned rare earth elements mining sites

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**ABSTRACT**

Hyperaccumulators harbor potentials for remediating rare earth elements (REEs)-contaminated soils. However, how they thrive in low-nutrient abandoned REEs mining sites is poorly understood. Three ferns (REEs-hyperaccumulators *Dicranopteris pedata* and *Blechnum orientale*, and non-hyperaccumulator *Pteris vittata*) along with their rhizosphere soils were collected to answer this question by comparing differences in soil nutrient levels, soil and plant REEs concentrations, and bacterial diversity, composition, and functions. Results observed lower soil pH (4.67–4.95 vs. 7.96), total carbon (TC) (0.35–0.62 vs. 2.84 g $kg^{-1}$), total nitrogen (TN) (20–23 vs. 133 mg $kg^{-1}$), and total phosphorus (TP) (81–91 vs. 133 mg $kg^{-1}$) at sites Dp and Bo than site Pv. Hyperaccumulators efficiently extracted soil REEs and translocated them to fronds (up to 6897–7759 mg $kg^{-1}$). Bacterial α diversity in three soils did not significantly vary. In contrast, bacterial composition at sites Dp and Bo was dominant by higher abundances of copiotrophic bacteria (18 % vs. 12 %, p_Actinomycetota; 3.3–8.3 % vs. 1.9 %, p_Bacteroidota; 8.3–14 % vs. 6.9 %, c_Gammaproteobacteria) and autotrophic bacteria (18 % vs. 13 %, p_Chloroflexota; 13 % vs. 8.6 %, p_Cyanobacteriota) when compared to site Pv. These bacteria likely acted as nutrient cyclers that promoted the growth of hyperaccumulators, based on functional predictions from DiTing analyses. This study provides new insights into nutrient recovery in abandoned REEs mining sites, offering strategies to reclaim degraded soils using phyto-microbial technology.

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# Metabolic flexibility of rhizobacteria drives soil nutrient cycling and enhances rare earth elements hyperaccumulation in ferns colonizing degraded mine ecosystems

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**ABSTRACT**

Rare earth elements (REEs) are crucial for green technologies, but their mining can severely degrade soil. While bacterial succession, often involving photoautotrophic and copiotrophic taxa, aids the colonization of REEs-hyperaccumulators in nutrient-poor soils, its applicability across plant ecotypes and light-limited conditions (e.g., winter) remains unclear. We compared two ferns (*Dicranopteris pedata* and *Blechnum orientale*) from core (DpM/BoM) and surrounding (DpS/BoS) areas, analyzing their REEs accumulation and rhizobacterial regulation of soil carbon (C) and nitrogen (N) cycling. Despite lower soil total REEs (5.28–9.37 times lower) and nutrients (TC ≤ 0.67 g $kg^{-1}$; TN ≤ 23.33 mg $kg^{-1}$), core ecotypes accumulated more REEs (e.g., 2765.03 vs. 131.67 mg $kg^{-1}$ Ce in *D. pedata*; 1486.22 vs. 660.90 mg $kg^{-1}$ La in *B. orientale*). The *r*/*K* life-strategy framework (copiotrophs vs. oligotrophs) did not fully explain microbial diversity and functions, as key taxa exhibited metabolic flexibility (e.g., chemoautotrophy). Core soils hosted copiotroph- and chemoautotroph-dominated microbiomes (p_Pseudomonadota, p_Actinomycetota, and p_Bacteroidota), linked to C/N cycling, whereas surrounding soils favored oligotrophs (p_Chloroflexota and p_Acidobacteriota). Both ferns enriched c_Alphaproteobacteria (especially g_*Bradyrhizobium*) and p_Actinomycetota (especially g_*Acidothermus*) for C/N fixation, these keystone taxa serve as potential biomarkers for monitoring soil nutrient recovery in REEs mining areas. Our findings indicate that microbial functional traits, beyond taxonomy, drive nutrient cycling in soils and REEs hyperaccumulation in plants, refining and expanding the *r*/*K* framework and suggesting seasonally tailored plant-microbe partnerships could optimize C/N cycling and enhance REEs phytoremediation in degraded soils.

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# Mechanistic Study of Rare Earth Element Bioleaching Mediated by Komagataeibacter xylinus

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**ABSTRACT**

Rare earth elements (REEs; scandium (Sc), yttrium (Y), and the 15 lanthanides—lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu)—are indispensable to modern technologies and emerging low-carbon systems. With rising demand and supply constraints, improving resource efficiency has driven interest in secondary REE sources beyond conventional mining. Industrial REE production typically relies on beneficiation followed by chemically intensive hydrometallurgy, including roasting/activation, strong-acid leaching (e.g., HCl, $H_2SO_4$, $HNO_3$), and downstream separation/purification. However, such flowsheets are often optimized for primary ores and can be less efficient for complex residual solids. Mine tailings can retain a non-trivial fraction of REEs after processing, making them a potentially valuable secondary resource for targeted recovery. Here, we investigate element-resolved REE bioleaching from REE-bearing tailings mediated by the heterotrophic bacterium *Komagataeibacter xylinus*, focusing on dissolution selectivity and cyclic stability. The tailings were wet and acidic and showed pronounced REE heterogeneity with relatively higher Nd, Dy, Er, Yb, and Y. Sequential fractionation concepts were used to interpret intrinsic mobility, where oxide-bound and residual associations generally indicate stronger mineral binding and lower immediate leachability. The tailings REEs were predominantly hosted in refractory Fe–Mn oxide–bound and residual fractions. Bioleaching was evaluated by comparing HR and HBR. Relative to HR, HBR substantially increased dissolved REEs dominated by Y, Nd, and Yb, with HREEs generally exceeding LREEs. Initial leaching efficiencies reached ~40%, while a three-cycle operation sustained release and increased cumulative efficiencies to ~80–92% for multiple elements while maintaining HREE enrichment. These results support K. xylinus–mediated bioleaching as a promising route for tailings valorization and secondary REE recovery.

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# Effects of different nitrogen fertilizer types on the remediation efficiency of Pteris vittata in arsenic-contaminated soil

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**ABSTRACT**

In the phytoremediation of arsenic (As)-contaminated soil, *Pteris vittata* has garnered significant attention due to its hyperaccumulation capabilities. However, the efficiency of remediation is greatly influenced by nutrient supply, with the type of nitrogen(N) fertilizer being a key regulatory factor. This study conducted a pot experiment to investigate the effects of three common N fertilizers—potassium nitrate, urea, and ammonium dihydrogen phosphate—along with a no-fertilizer control (CK) on the growth, As uptake, and soil physicochemical properties of *Pteris vittata*. The results indicated that fertilization significantly enhanced both biomass and As accumulation in *Pteris vittata*. Urea treatment exhibited the greatest efficacy in promoting biomass growth and As absorption, achieving the highest remediation efficiency. While potassium nitrate treatment had a relatively minor impact on soil pH, it still significantly enhanced remediation efficiency. Although ammonium dihydrogen phosphate effectively mobilized soil As, it posed a risk of phosphorus(P) accumulation and led to a notable decrease in soil pH. Overall, urea is recommended as the preferred N fertilizer for improving the remediation efficiency of *Pteris vittata*, although long-term application should be approached with caution due to potential soil acidification and P pollution risks. This study provides a theoretical foundation for the scientific selection of N fertilizers in the remediation of As-contaminated soil.

**Acknowledgments**

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# Multi-Pathway Synergy Drives Rapid Soil Fertility and Crop Yield Improvement in Newly Reclaimed Cropland: The Role of Integrated Soil Improvement

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## ABSTRACT

Newly reclaimed cropland commonly faces issues such as poor soil structure, low fertility, and insufficient biological activity, which constrain crop production. However, the comprehensive effects of different soil improvement measures on various aspects of soil health and their relationship with crop growth remain unclear. To address this, a field experiment was conducted with the following treatments: chemical fertilizer alone (NPK), bio-organic fertilizer (MF), two integrated improvement measures (MCN and MCN_2), and a blank control (CK). Both the bio-organic fertilizer and the two integrated measures were amended with an equivalent amount of organic matter. The integrated measures comprised an organic material source combined with modified biochar, minerals, and microbial inoculants. The study aimed to investigate the effects of these different treatments on soil physical, chemical, and biological properties as well as wheat growth, and to identify key soil factors driving yield improvement. Measurements at wheat maturity showed that, compared to the NPK treatment, the MCN treatment was most effective in improving soil structure (bulk density reduced by 0.14 g/cm³), alleviating acidification (pH increased by 0.87 units), enhancing fertility (soil organic matter increased by 4.43 g/kg, the ratio of available phosphorus to total phosphorus increased by 3.5%, and calcium content increased by 0.07%), and boosting microbial richness (Observed, Chao1, and Shannon indices increased by 28.6%, 28.3%, and 7.3%, respectively) and activity (activities of β-glucosidase, leucine aminopeptidase, and β-N-acetylglucosaminidase increased by 106.1%, 29.7%, and 60.0%, respectively). LEfSe analysis revealed that the integrated treatments enriched nitrogen-fixing bacteria (e.g., *Mesorhizobium*), organic matter-decomposing bacteria (e.g., *Fibrobacteraceae*, *Pseudohongiellaceae*), and beneficial *Bacillus* strains (e.g., *Blastocatellaceae*). Furthermore, the MCN treatment significantly increased wheat plant height, stem diameter, and yield, resulting in yield increases of 294.3% and 16.5% compared to the NPK and MF treatments, respectively. Correlation analysis indicated that grain yield was significantly correlated ($p < 0.05$) with soil organic matter, total nitrogen, total phosphorus, available phosphorus, calcium, manganese, the Shannon index, and bacterial phyla including *Pseudomonadota*, *Verrucomicrobiota*, and *Actinomycetota*. Yield also showed positive correlations with soil pH and the activities of sucrase, β-glucosidase, leucine aminopeptidase, and β-N-acetylglucosaminidase. Partial least squares path modeling identified the core pathway as "Improvement measures → Enhanced soil fertility (increased organic matter and mineral elements) → Microbial regulation → Yield promotion." In conclusion, the integrated measure combining organic materials with modified biochar, minerals, and microbial inoculants can rapidly improve soil health and crop yield in newly reclaimed cropland through synergistic multi-pathway effects, representing an effective strategy for achieving rapid maturation and ensuring high, stable yields in such soils.

**Key words:**Newly reclaimed cropland, Soil health improvement, Drivers of crop productivity, Multi-pathway synergy

# Qualidade e saúde do solo: bases para a transição agroecológica em agroecossistemas

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**ABSTRACT**

A qualidade e a saúde do solo são componentes essenciais para a sustentabilidade dos agroecossistemas e para o fortalecimento da transição agroecológica, pois expressam a capacidade do solo em sustentar a produtividade biológica, manter a qualidade ambiental e promover a saúde das plantas, dos animais e das populações humanas. Na abordagem agroecológica, o solo é compreendido como um sistema vivo e dinâmico, cuja avaliação deve integrar atributos químicos, físicos e biológicos. Nesse contexto, sistemas de semeadura direta de longa duração, especialmente em Latossolos Vermelhos Distroférricos, contribuem para a conservação da estrutura, o acúmulo de matéria orgânica e o estímulo à atividade microbiana. O objetivo foi avaliar a qualidade e a saúde do solo em sistema de cultivo aveia preta/soja, utilizando análises químicas e físicas do solo e a Cromatografia Circular de Pfeiffer (CCF). O estudo foi realizado em uma Unidade de Produção Agrícola no município de Ijuí, Rio Grande do Sul (RS) - Brasil. As amostras de solo foram coletadas nas camadas de profundidades de 0–10, 10–20 e 20–40 cm.

Os resultados indicaram boas condições químicas do solo, com acidez controlada e teores adequados de bases trocáveis, além de clara estratificação de fósforo, potássio e matéria orgânica, característica do manejo em semeadura direta. A densidade do solo e a porosidade total revelaram estrutura estável na camada superficial (0–10 cm), compactação moderada na camada de 10–20 cm e leve recuperação estrutural em 20–40 cm. A umidade volumétrica aumentou em profundidade, refletindo maior retenção de água e redução do espaço aéreo, que se manteve adequado às trocas gasosas e à atividade biológica.

A cromatografia circular indicou elevada atividade biológica e boa organização estrutural na camada superficial, redução da atividade na camada intermediária e menor dinamismo biológico na camada mais profunda. Conclui-se que o sistema de manejo adotado favorece a sustentabilidade e a qualidade do solo, contribuindo para a produtividade agrícola e a transição agroecológica.

**Agradecimentos**

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# Phytate-Mediated Arsenic Hyperaccumulation in Pteris vittata: Synthesis, Sequestration, and Exudation

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## ABSTRACT

Phytate enhances arsenic metabolism in As-hyperaccumulator *Pteris vittata*, but the underlying mechanisms remain unclear. Using *P. multifida* and *P. ensiformis* as comparisons, we investigated the plant growth, As/P uptake, and phytate synthesis, sequestration, and exudation in *P. vittata* under 10-100 μM As exposure. The expressions of P transporters Pht1;2-1;4, phytate synthesis genes including myo-inositol 3-phosphate synthase (*MIPS*), myo-inositol monophosphatase (*IMP*), and 2-phosphoglyceric acid kinase (*2-PGK*), and phytate transporter multidrug resistance-associated protein 5 (*MRP5*) were analyzed. After 3 weeks of growth, *P. vittata* accumulated the greatest As in the fronds at 155-3098 mg $kg^{-1}$, with biomass being increased by 9.8–63%. While greater expression of PvPht1;2-1;4 helped *P. vittata* to maintain stable plant P contents at 3005-3552 mg $kg^{-1}$, PmPht1;2/1;4 and PePht1;2/1;4 expression was reduced by 10–55%. Arsenic exposure enhanced phytate accumulation in *P. vittata* by upregulating phytate synthesis genes MIPS, IMP and 2-PGK and phytate transporter gene MRP5 by 1.3-1.7 fold, increasing phytate contents by 1.1-2.1 fold to 69.2-371 mg $kg^{-1}$. Further, *P. vittata* increased phytate root exudation by 1.5-3.6 fold under As exposure, whereas *P. multifida* and *P. ensiformis* mainly exuded tartrate. In short, As-enhanced phytate metabolism in *P. vittata* is unique and contributes to its superior As-accumulation ability, showing implication for phytoremediation of As-contaminated soils.

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# Soil quality in a long-term Tifton 85 pasture overseeded with forage radish and annual ryegrass

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**ABSTRACT**

This study evaluated soil quality in a long-term Tifton 85 pasture, overseeded with forage radish and naturally reseeded ryegrass. The assessment was carried out through the integration of physical, chemical, and biological indicators, including qualitative measures such as Pfeiffer Circular Chromatography. This is a qualitative and semi-quantitative method primarily used to assess soil biological quality in agroecological contexts, biodynamic agriculture, and soil health studies. The physicochemical analyses revealed a pattern typical of perennial systems, characterized by higher soil quality in the surface layer (0–10 cm), with greater organic matter contents, lower soil bulk density, and higher air-filled porosity. In contrast, deeper layers (10– 20 and 20–40 cm) showed increased compaction, reduced organic carbon, lower phosphorus availability, and decreased porosity. The chromatograms corroborated these results by indicating high biological vitality and good structural integration in the surface layer, followed by a progressive reduction in microbial activity and colloidal stability with increasing depth. The complementarity between alternative methods and conventional indicators broadened the functional understanding of the soil, demonstrating that the integrated use of qualitative and quantitative tools enhances diagnostic sensitivity, especially for detecting changes in structural and biological attributes that are not evident when assessed in isolation by traditional analyses. The study showed that the evaluated system presents good surface soil (edaphic) functionality, resulting from the continuous input of roots, plant residues, and nutrient cycling promoted by forage species. However, limitations persist in subsurface layers, such as reduced effective rooting depth, moderate compaction, and low phosphorus availability. These conditions indicate the need to adopt management practices that enhance biological activity at depth, such as the strategic use of plants with taproot systems, appropriate grazing management to reduce soil compaction, and improvements in subsurface fertility. It is concluded that the combined use of Pfeiffer Circular Chromatography and physicochemical analyses constitutes a robust and efficient approach for assessing soil quality and health in long-term forage systems, providing essential support for the implementation of more sustainable, resilient, and conservation-oriented management practices.

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# Re-thinking Climate Resilience in Smallholder Agriculture: Insights from Technology, Economics, and Policy Interactions in Eastern India

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**ABSTRACT**

Agriculture is the backbone of Bihar's economy and a critical component of India's food production system, forming an integral part of the eastern Indo-Gangetic Plains, one of the most densely populated and climate-vulnerable agricultural regions of the world. supporting more than 70% of the population; however, the sector is increasingly threatened by climate variability, rising input costs, and uneven adoption of modern technologies. This study evaluates the interlinkages among technology adoption, economic constraints, climate resilience, policy awareness, and income stability across Bihar's four agro-climatic zones (ACZ-I, ACZ-II, ACZ-IIIa, and ACZ-IIIb). Primary data were collected from 2,000 farmers across seven districts using a structured survey framework. Composite indices including Yield Impact Score (YIS), Technology Adoption Index (TAI), Input Cost Index (ICI), Climate Resilience Index (CRI), Policy Awareness Index (PAI), and Income Stability Index (ISI) were developed to assess spatial and socio-economic disparities. Results revealed pronounced inter-zonal variability. ACZ-II emerged as the most resilient zone, with the highest TAI (5.9), CRI (6.8), and ISI (4.5), supported by improved access to credit, mechanization, climate-smart varieties, and post-harvest infrastructure. In contrast, ACZ-I and ACZ-IIIb experienced high input cost escalation (26.7–28.9%), lower technology adoption, and reduced income stability. Regression analysis identified technology adoption as the strongest positive driver of climate resilience ($\beta = +0.45$, $p < 0.01$), followed by income stability ($\beta = +0.30$, $p = 0.06$), while high input costs exerted a significant negative effect ($\beta = -0.25$, $p < 0.05$). Spatial analysis using QGIS highlighted clear hotspots of vulnerability and resilience across agro-climatic zones.

The findings underscore that climate resilience in Bihar is not solely technology-driven but depends on an integrated approach combining affordable inputs, credit access, policy outreach, and market linkages. Strengthening extension services, scaling climate-smart technologies, and improving post-harvest infrastructure are critical to enhancing resilience and ensuring sustainable agricultural development in climate-vulnerable regions.

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# Adapting to Climate Change: Sustaining Soil Health through Carbon-Nitrogen Cycle Management

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**ABSTRACT**

Future climate change is projected to have profound impacts on global soil health, with the response and feedback mechanisms of carbon-nitrogen (C-N) cycles playing a particularly critical role. Soils serve as major sources and sinks of carbon and nitrogen in terrestrial ecosystems, yet the key processes governing C-N cycling are highly complex and remain among the most uncertain components of climate-change response mechanisms. This uncertainty substantially constrains the accuracy of future C-N dynamic predictions and undermines the reliability of soil health assessments.

To address this challenge, this study integrates observational data from multi-site climate-change manipulation experiments worldwide to construct a systematic database. Combined with process-oriented C-N cycle models, we systematically analyze the key pathways through which climate change affects soil C-N transformation, storage, and loss. Building on this, we further develop an integrated soil health indicator system encompassing physical, chemical, and biological attributes, and evaluate the multidimensional impacts of different climate-change scenarios—such as warming, precipitation variation, and elevated $CO_2$ concentrations—on soil health.

The results demonstrate that climate change, by altering the balance of C-N cycles, significantly affects soil organic matter stability, nutrient availability, and microbial functionality, thereby threatening the long-term maintenance of soil health. Finally, this study proposes climate-adaptation strategies centered on sustainable soil resource management. These strategies emphasize enhancing soil resilience to climate change through optimized agricultural practices, restoration of ecosystem functions, and increased soil organic carbon sequestration capacity. The findings provide a scientific basis for achieving global land sustainability and supporting climate mitigation and adaptation goals.

# Reinventing Soil Health in the Plastic Age: Fungal-Nano Synergies for Microplastic Remediation

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**ABSTRACT**

Microplastic contamination is now recognized as one of the most persistent and underestimated dangers to soil ecosystems with agricultural soils as significant long-term sinks. Polymer residues accumulate and affect soil structure, microbial functioning, nutrient cycling and plant performance, posing concerns to food security and human health. Traditional remediation procedures remain costly, inadequate, and detrimental to the environment, emphasizing the critical need for scalable, soil-compatible alternatives. This paper presents recent breakthroughs in fungal bioremediation combined with nano-enabled technology as a next-generation technique for mitigating soil microplastic contamination. Filamentous fungi such as *Aspergillus niger, Aspergillus terreus, Penicillium chrysogenum, Fusarium solani, Trichoderma harzianum*, and white-rot fungi like *Phanerochaete chrysosporium* and *Trametes versicolor* have a unique ability to colonize hydrophobic plastic surfaces and enzymatically depolymerise recalcitrant polymers like polyethylene, polystyrene, and polyurethane. These fungi secrete oxidative and hydrolytic enzymes, such as laccases, manganese peroxidases, esterases, and cutinases, which cause polymer oxidation, chain scission, and biofragmentation. However, fungal decomposition alone is typically limited by slow reaction kinetics, partial mineralization and environmental unpredictability in field circumstances. Recent nano-enhanced techniques provide an effective way to circumvent these restrictions. Photocatalytic nanoparticles including titanium dioxide ($TiO_2$), zinc oxide (ZnO), iron oxide ($Fe_3O_4$) and graphitic carbon nitride (g-$C_3N_4$) produce reactive oxygen species that pre-oxidize polymer chains, enhancing fungal accessibility and enzymatic efficiency. Enzyme immobilization on silica nanoparticles, magnetic $Fe_3O_4$ nanocarriers, graphene oxide and biochar-based nanocomposites improve enzyme stability, recyclability and polymer-enzyme interaction. Emerging myco-nano hybrids, such as fungal-biosynthesized metal nanoparticles and nanoparticle-decorated mycelial networks, exhibit synergistic degrading capability while minimizing ecotoxicological concerns. Advances in analytical validation such as FTIR, Raman spectroscopy, Py-GC/MS, and electron microscopy now allow for precise differentiation between real biodegradation and physical fragmentation. The remaining challenges such as nanoparticle fate, by-product toxicity, consequences on non-target soil biota and large-scale field deployment are thoroughly examined. This work outlines a forward looking remediation paradigm with global relevance by bridging soil microbiology, nanotechnology and sustainable agriculture. It establishes fungal-nano systems as a cornerstone technology for restoring soil health, informing environmental policy and advancing resilient agri-food systems as an impact that extends far beyond disciplinary boundaries.

**Keywords:** Soil microplastics, Fungal bioremediation, Nano-enhanced remediation, Soil health and sustainability

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# Digital Characterization of the Spatial Distribution of the Albic Horizon in the Northeast Black Soil Region

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## ABSTRACT

This study aims to clarify the spatial distribution, characteristics, and multi-factor driving mechanisms of the albic horizon—a critical soil constraint layer in the Northeast Black Soil Region, which serves as China's premier grain production base. The albic horizon, characterized by high bulk density, elevated hardness, and shallow burial depth, severely restricts plant root penetration and hydrological processes, hindering sustainable agricultural development in this strategically important region. Taking the Northeast Black Soil Region as the research area, a soil profile dataset was constructed by integrating measured data from 5 field-investigated standard profiles and systematically compiled records from 776 historical survey profiles. Combined with 21 environmental covariates spanning 7 categories (including climate, topography, hydrology, and soil properties), a random forest (RF) machine learning model was applied to quantitatively analyze the spatial distribution and characteristics of the albic horizon. The results showed that the albic horizon was mainly distributed in the Sanjiang Plain (covering Jiamusi, Shuangyashan, and Jixi), the northern foothills of the Changbai Mountains (including Mudanjiang, Hegang, and Harbin), and the central low mountain-hilly terrain of Jilin (encompassing Liaoyuan, Tonghua, and Yanbian), with a total predicted area of approximately 29,100 km$^2$ (model Kappa coefficient=0.87, indicating excellent predictive accuracy). In terms of characteristics, the burial depth exhibited a distinct "deep northeast, shallow southwest" spatial gradient: deeper zones concentrated in the Sanjiang Plain interior and central Jilin hilly regions, while shallower zones occurred in the southern Wanda Mountain foothills and western Changbai Mountain foothills, with burial depths ranging from 13.44−38.29 cm. Thickness showed a "thicker central, thinner peripheral" pattern: thick layers mainly located in the eastern Songnen Plain and western Zhangguangcai Mountain foothills, while thinner layers distributed along the southern Xiao Hinggan Mountain foothills and northern Liaoning Horqin Sandy Land margins, with thickness spanning 12.98−33.36 cm. Multivariate analysis identified key environmental drivers: climate-topography interactions primarily regulated burial depth, hydrology-geomorphology-biology synergies shaped thickness spatial patterns, and soil property-climate-topography interactions dominated albic horizon occurrence and distribution. This study establishes a robust digital characterization framework for the albic horizon and accurately delineates its spatial distribution patterns alongside multi-factor driving mechanisms. The findings provide a scientific foundation for developing differentiated black soil conservation and restoration strategies, which hold profound implications for sustainable black soil resource utilization and regional food security assurance.

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# EcoPond: A Nature-Based Solution to Reduce Methane Emissions from Animal Effluent and Manure Storage Systems

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**ABSTRACT**

Methane ($CH_4$) emissions from animal effluent ponds and manure storage systems represent a significant source of agricultural greenhouse gases (about 10-15% of methane emissions from animal production systems), contributing substantially to global climate change. Traditional manure management practices often rely on anaerobic decomposition, which generates methane ($CH_4$) as a by-product. The EcoPond technology offers an innovative, low-cost, and scalable approach to mitigating methane emissions by inhibiting methanogenesis within effluent storage systems.

EcoPond employs a targeted, environmentally benign food additive treatment, using poly-ferric sulphate (PFS) and sulphuric acid, that disrupts the activity of methane-producing microbes without negatively impacting nutrient recycling or the downstream use of effluent as a nutrient source. The technology is applied directly to effluent ponds or storage tanks, rapidly creating a microbial environment that favours alternative pathways over methanogenesis. This intervention results in a substantial reduction in methane production during storage, with field trials demonstrating reductions averaging about 96%.

Multiple on-farm studies have evaluated EcoPond across diverse climatic regions, animal production systems, and pond configurations. These trials have consistently shown significant methane suppression within days of application, sustained over several months. Importantly, the treatment does not adversely affect effluent nutrient content, allowing for continued use in soil nutrient management plans without adversely affecting nutrient availability or microbial populations. Furthermore, the treatment also significantly reduce phosphate leaching and E coli leaching by more than 90% when the treated effluent is applied back to the soil to recycle nutrients. EcoPond represents a valuable tool in integrated nutrient and greenhouse gas management, aligning with climate-smart farming practices. By reducing methane emissions at the storage stage, the technology addresses a critical gap between farm productivity and environmental stewardship. Widespread adoption of EcoPond could contribute material greenhouse gas reductions, while maintaining soil fertility and water quality outcomes.

This paper presents the underlying mode of action of EcoPond, experimental design and methodologies for emission measurement, and results from on-farm trials. The findings highlight the potential for targeted microbial management to transform manure storage from a major methane source into a more climate-resilient component of agricultural nutrient cycles.

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# Effect of cover crops on carbon and nitrogen stocks in perennial crops under Mediterranean conditions

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**ABSTRACT**

The intensification of agricultural systems leads to soil degradation, posing a serious risk to sustainable food production. The use of cover crops is a strategy for climate change adaptation and mitigation, as they contribute to carbon sequestration. This study examined the effects of cover crops on carbon contents and stocks at 0-1 m depth in fruit and olive tree crops in southeastern Spain. To this end, 12 commercial farms (6 olive groves and 6 fruit orchards) were selected. For each crop type, farms with cover crops (6-19 years of implementation) were compared with farms that maintained soil bare through tillage and herbicides application. The treatments were: olive grove with cover crops (OCC), olive grove with bare soil (OBS), fruit trees with cover crops (FCC), and fruit trees with bare soil (FBS). In each plot, six profiles were opened, and soil samples were collected from each genetic horizon. The soil profiles had an average depth of 100 cm, with four horizons identified in each profile. Bulk density (BD), soil organic carbon (SOC), and total nitrogen (TN) were analyzed to calculate soil organic carbon (SOC stocks) and total nitrogen (TN stocks) stocks. The results showed an increase in stocks in the surface horizon (Ap) under cover crops in both crop types. In olive groves, OCC showed a higher SOC stock in A horizon (27.34 Mg $ha^{-1}$) compared to OBS (16.29 Mg $ha^{-1}$). In fruit trees, FCC showed a SOC stock of 29.03 Mg $ha^{-1}$ in the A horizon, significantly higher than FBS (11.54 Mg $ha^{-1}$). The TN stock in topsoil followed a similar trend, also being significantly higher in the plots with cover crops. However, when considering the complete profile, the total stocks showed different patterns. In fruit trees, FCC showed higher SOC stock (99.73 Mg $ha^{-1}$) compared to FBS (78.53 Mg $ha^{-1}$). In contrast, in olive trees, OBS had higher SOC stock (111.19 Mg $ha^{-1}$) than OCC (82.76 Mg $ha^{-1}$). The TN stock followed the same pattern than SOC stock in both crops. Therefore, the effects of cover crops were mainly observed in topsoil (Ap), with higher SOC and TN stocks than on farms with bare alleys. Thus, cover crops contributed to C sequestration and storage only at 0-20 cm depth after more than 6 years of implementation. This study also shows the importance of studying deeper horizons, as their exclusion from the analysis could lead to misleading conclusions.

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# Optimizing sampling protocols for agriculture and soil science: introduction of a spatial machine learning decision support tool

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**ABSTRACT**

Spatial soil/crop mapping by remote sensing products, together with proximal sampling and/or sensors, provide data important for decision-making, particularly regarding precision agriculture. However, the high cost of sensors and sampling limits their use and reduces the accuracy of spatial representation. Additionally, spatial autocorrelation affects sampling efficiency, indicating redundancy when samples close to one another are similar. When planning sensor or sampling point distribution, questions to be addressed include: (a) the minimum number of sensors/samples required, (b) the location and distribution of samples in the field that accurately represent the spatial variability, and (c) the environmental variables that should be considered in the process.

We present a model and decision support tool (DST) that represents spatial variability using stratified-based sampling by integrating multi-variable spatial-statistical analysis with machine learning. The model is based on and accounts for: (a) stratified-based sampling in which management zones (MZs) act as confining sub-regions, (b) local spatial autocorrelation, and (c) correlation between predicting and predicted (to be sampled) variables. The calculated degree of spatial correlation in each MZ determines the number of samples. The distribution of samples is based on spatial histograms and interpolating the selected samples to assess configuration errors. A web-based DST outputs maps based on optimal spatial placement of sensors or samples within a field, indicating the required number of samples and quantifying accuracy levels for configurations using fewer samples. Progress and opportunities currently available, as well as remaining issues and challenges, both theoretical and regarding the model's practical application, will be discussed.

**Acknowledgments**

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# Pathways to resilience in dryland agricultural systems

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**ABSTRACT**

Agricultural systems are facing escalating challenges from increased climate variability, particularly due to the rising frequency and intensity of extreme weather events. Despite academic progress in defining farm resilience, current research has often focused too much on setting system boundaries, which might not translate into practical operational measures at the farm level. In this study, we used the APSFarm model to simulate the likely pathways for 3 case study farms, aiming to understand how extreme climate influences farm resilience indicators and how to bridge the gap between academic resilience theories and farm management practices.

A conceptual whole farm-level resilience framework that integrates adaptive cycles and multi-level analyses was developed. The framework focuses on six cyclical key steps: 1) defining vulnerable farm components, 2) identifying the frequency and intensity of stressors, 3) setting resilience goals, 4) quantifying farm resilience capacities and responses to stressors, 5) determining tipping points, and 6) feedback and enhancing resilience attributes. Interviews with high-performing farmers and well-known private consultants were used to learn about present farmers' coping mechanisms and to parameterise and validate the whole farm model APSFarm Next Gen. Long-term climate records were analysed to identify critical climate factors and their tipping points using Gradient Forest and Spearman correlation analyses. Future climate scenarios were used to introduce stress on the simulated case study farms, study resilience responses to stressors, and identify tipping points. Feedback meetings with the participating farmers and consultants were used to discuss opportunities to optimise agricultural practices.

**Acknowledgments**

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# Impacts of Corn Hybrid and Fertilization Strategies on Plant Carbon Allocation and Soil Carbon Dynamics Under Variable Moisture Conditions

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**ABSTRACT**

Intensive agricultural activities deplete soil organic carbon (SOC) stocks in global croplands. A thorough understanding of how management practices impact SOC dynamics is essential for developing effective strategies to rebuild C stocks. This study investigates how corn hybrids (Bayer tall- and short-statured) and nitrogen (N) fertilizer strategies (rates and types) influence root exudation, belowground C inputs, and soil C pools (microbial biomass and total C) in different soil types and moisture conditions in a greenhouse and field studies. By analyzing C allocation between above- and belowground components, as well as root exudation and soil microbial C, we aim to determine whether belowground C inputs can be enhanced through hybrid selection and fertilization strategies. Findings reveal that short-statured corn exhibited greater belowground root biomass and root length compared to tall-statured corn, while excessive N tended to diminish these benefits. These trends were consistent with several other observations, including soil microbial biomass C responses to N fertilization, particularly in loamy soils. However, root exudate C did not show a consistent trend with increasing N rates. Overall, this study provides mechanistic insights into the 'Surplus Plant C Theory', which suggests that crop-soil-microbe interactions can be optimized through intermediate levels of N fertilization to enhance soil C accumulation. Further research is needed to validate these findings under diverse field conditions.

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# Innovative Pasture Diversification Trials to Enhance Soil Health, Carbon Dynamics, and Climate Resilience

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**ABSTRACT**

Pasture systems across the world face increasing pressures from climate variability, soil degradation, and declining productivity. Developing resilient and diversified pastures is therefore critical for sustaining agricultural output while enhancing soil health and carbon storage. In response, the University of Western Australia (UWA) and the Department of Primary Industries and Regional Development (DPIRD) have launched a three-year field program to trial and demonstrate the benefits of innovative pasture species diversification across WA's high- and low-rainfall zones with funding support from the Department of Agriculture, Fisheries and Forestry. Five demonstration sites were established to evaluate combinations of perennial and annual legumes and grasses, including *Tedera* (*Bituminaria bituminosa*), *Lucerne* (*Medicago sativa*), and cocksfoot (*Dactylis glomerata*), under contrasting environmental conditions. Each site follows a replicated experimental design with standard fertiliser, weed-control, and defoliation regimes to ensure robust assessment of pasture productivity, soil improvement, and climate resilience.

Soil sampling and laboratory analyses quantify physicochemical and biological properties, including nutrient dynamics and organic-carbon fractions, while bioinformatics tools are applied to evaluate microbial community structure and function. High-resolution imagery complements field observations to track pasture establishment, canopy cover, and temporal trends in productivity. Carbon movement and storage potential are modelled to build a systems-level understanding of diversified pasture performance under variable climates.

This initiative builds on previous UWA-DPIRD collaborations in soil restoration and carbon farming, introducing a novel combination of soil bioinformatics, and carbon modelling to evaluate pasture diversification as a climate-smart practice. By coupling on-farm demonstration with advanced analytical approaches, the project will generate evidence-based recommendations for improving soil health, enhancing carbon dynamics, and supporting producer adaptation to a variable climate. Outcomes will directly inform WA's climate-smart agriculture strategies and provide a transferable framework for sustainable pasture management across southern Australian mixed-farming systems.

**Keywords:** Climate resilience, Diverse crops, Carbon dynamics

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# Does a long-term no-till corn-soybean rotation decrease nitrous oxide emissions in Alfisols?

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**ABSTRACT**

Switching from conventional tillage operations to no-till often improves soil properties long-term, but effects on nitrous oxide ($N_2O$) emissions are less known. The objective of this study was to determine the influence of tillage practices on soil properties, $N_2O$ emissions, and corn (*Zea mays* L.) and soybean (*Glycine Max* L.) yields after 49-52 years of continuous treatment implementation in a long-term corn-soybean rotation experiment in southern Illinois, USA. The experimental design was a randomized complete block design replicated four-times with four treatments. Treatments were two tillage systems, chisel tillage (RT) and no-tillage (NT). Each tillage system received either no-fertilizer (control) or was fertilized with 196 kg N $ha^{-1}$, 24 kg P $ha^{-1}$ and 140 kg K $ha^{-1}$ during the corn years (optimum fertility). No fertilization was applied during soybean years. Nitrous oxide was measured prior to field operations (baseline sampling), after planting, and during corn and soybean growing seasons. Our results indicated that no-till resulted in similar corn grain yield at optimum fertility but higher $N_2O$-N emissions in RT-NPK during the corn year. Soybean yields were higher in NT than RT with $N_2O$-N emissions being similar over the two years. Over a four-year period, we also observed that NT resulted in a reduction in $N_2O$-N emissions and yield-scaled $N_2O$-N emissions. Therefore, we suggest NT can be implemented to provide environmental and soil benefits in corn-soybean rotations.

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# Neglecting Non-Rainfall Water Contributions Results in an Overestimation of Crop Water Use Efficiency

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**ABSTRACT**

Non-rainfall water (NRW)—including dew, fog, and vapor adsorption—constitutes a hidden yet critical component of cropland water input that is often overlooked in hydrological and agricultural assessments. Using multi-year observations from eight long-term experimental stations across China, this study quantified the magnitude, variability, and climatic controls of NRW across ten representative cropland types, including millet, soybean, spring corn, winter wheat, and peanut. Continuous measurements of meteorological variables, evapotranspiration (ET), and soil temperature were analyzed using structural equation modelling (SEM) and SHAP-based attribution to disentangle direct and indirect climatic influences on NRW formation and its contribution to the crop water balance. Results showed that NRW accounted for 3–12% of total water inputs and 5–18% of ET, with nighttime condensation being the dominant process. Relative humidity and radiative cooling were identified as the strongest positive drivers, while wind speed and vapor pressure deficit exhibited negative effects. SEM analysis revealed that temperature and humidity jointly mediated surface energy exchange, reinforcing nocturnal cooling essential for condensation. Regional differences in factor sensitivity reflected local climate regimes rather than crop-specific variations, indicating that NRW represents a stable supplementary water source under precipitation variability. When NRW was excluded from the water balance, the calculated crop water use efficiency (WUE)—defined as the ratio of net primary productivity to total water input—was systematically overestimated, particularly in semi-arid regions where NRW contributions were highest. Incorporating NRW into water accounting improves the consistency between evapotranspiration and total water input, providing a more accurate estimation of water use efficiency under variable climate conditions. These findings highlight the need to treat NRW as a routine component of the water budget, improving field-scale water-use assessment and guiding adaptive irrigation management.

# Soil Carbon Cycle and Carbon Sequestration Strategies in Saline-Alkali fields

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## ABSTRACT

We researched carbon cycle processes in saline-alkali soils in the oasis agricultural ecosystem of the Tarim River Basin. Through a combination of laboratory analyses and field observations, we systematically examined soil $CO_2$ emission characteristics, identified key transport mechanisms and influencing factors, and elucidated the phenomenon of negative $CO_2$ flux observed. The results demonstrate that inorganic carbon absorption increases with decreasing temperature, rising alkalinity, and higher partial pressure of $CO_2$. Furthermore, microbial activity, soil flooding conditions, and reduced salinity collectively affect soil $CO_2$ concentration and suppress the recrystallization of calcium carbonate.

In addition, our research specifically addressed carbon cycling in agricultural ecosystems by assessing greenhouse gas emissions, soil organic carbon sequestration, and the carbon footprint under varying water and fertilizer management practices. Our findings suggest that integrating biochar amendment with reduced water and fertilizer inputs represents a viable strategy for achieving water-efficient, low-carbon, and sustainable agricultural development in saline-alkali regions.

# Interactive effects of straw and biochar amendments on soil organic carbon stabilization and bacterial community dynamics

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**ABSTRACT**

Organic amendments such as straw and biochar are widely applied to enhance soil fertility, yet their distinct contributions to soil organic C (SOC) stabilization remains poorly understood. Through a 180-day laboratory incubation experiment, we quantified and compared the effects of two straw amendment strategies—direct straw incorporation and straw-derived biochar application—on SOC stabilization across different soil types, with a focus on the underlying chemical and microbial mechanisms. This study revealed that biochar-treated soils exhibited significantly lower SOC mineralization than straw-treated soils. Furthermore, biochar-straw co-application demonstrated greater efficacy in suppressing C losses relative to straw alone, with reductions of 49% in sodic solonchaks and ~25% in cambisols. This reduction was attributed to biochar's inherent resistance to microbial degradation, strong adsorption of ammonium nitrogen, and reduced dissolved organic C availability. These effects highlight biochar's dual role as both a biologically inert C pool and an active regulator of soil nutrient dynamics. Notably, biochar application promoted SOC stabilization by increasing the aromatic-to-aliphatic C ratio (quantified as relative absorbance ratio of 1630 $cm^{-1}$ to 2920 $cm^{-1}$, rA1630/rA2920), indicating enhanced aromatic C accumulation while suppressing bacterial activity and aliphatic C formation. In contrast, direct straw incorporation stimulated microbial growth, increasing microbial residue C accrual, its contribution to SOC (~13%), and the fungal-to-bacterial residue C ratio, suggesting distinct SOC stabilization via microbial residue formation. Straw amendment significantly enhanced microbial residue C accumulation by ~20% relative to controls and biochar treatments, where biochar-treated soils showed microbial residue C levels similar to controls. Notably, under straw amendment, cambisols exhibited a 1.5-fold greater microbial residue contribution to SOC than sodic solonchaks. These findings demonstrate a fundamentally different SOC stabilization mechanisms: biochar enhances chemical stabilization through aromatic C enrichment, whereas straw fosters biological stabilization through microbial residue accumulation. Moreover, the ability of biochar to mitigate nutrient-induced SOC destabilization underscores its potential for reducing soil $CO_2$ emissions and advancing sustainable soil C management.

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# Short rotation coppice on degraded and fertile soils

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**ABSTRACT**

Our research examines the productivity and growth of short-rotation coppice (SRC) species in an alley-cropping system on soils of varying quality and under different mulching treatments at the experimental site of the Faculty of Agrobiotechnical Sciences Osijek, Croatia. In 2021, an SRC trial was established with willow (*Salix alba* L.) and poplar (*Populus* spp.). Trees were planted in four 8-m belts, each with six rows spaced 1–2 m apart, separated by 24-m alleys for machinery access. Belts were 100 m long, with 50-m sections assigned to each species. A control plantation was located on the southern edge, and a canal bordered the western side.

The study evaluated growth performance and biomass productivity of willow and poplar across four soil treatments: degraded soil, fertile soil, fertile soil with straw, and fertile soil with nylon mulch. This setup enabled analysis of how soil quality and mulching influence SRC development. Biomass sampling was conducted in 2025, while tree height was measured in 2021, 2023, and 2024.

During the four years (2021-2025), poplar consistently produced more biomass than willow across all soils. Poplar performed best on fertile soil without mulch (50,05 t/ha), though mulch with nylon (42,55 t/ha) and mulch with straw (38,90 t/ha) also supported strong growth. Willow showed its best growth on fertile soil with nylon (26,32 t/ha), likely due to improved moisture retention and reduced weed pressure. Straw mulch was the least effective for willow (2,21 t/ha), limiting water and air availability and resulting in the lowest yields. Degraded soil produced moderate but acceptable growth (willow – 11,90 t/ha; poplar – 28,63 t/ha) in comparison to the control (willow – 5,00 t/ha; poplar – 17,71 t/ha).

Height measurements from 2021–2024 supported these patterns: nylon mulch benefited willow heights, while poplar was highest on fertile soil without any mulch. Statistical analyses confirmed significant differences among treatments, emphasizing the importance of soil quality and mulch choice.

Biomass data from 2021 and 2025 further showed that soil quality determined yield. Fertile soil produced the highest biomass, with nylon mulch offering notable gains, especially for willow. Mulch treatments showed that straw-covered blocks consistently had the lowest yields, although poplar performance on straw improved by 2025. Overall, findings demonstrate that alley-cropping systems with fast-growing SRC species such as willow and poplar provide an effective approach to producing renewable raw materials. They also offer potential for rehabilitating and economically using degraded or marginal soils, contributing to more resilient and diversified land-use systems.

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# Effects of combined application of biochar and manure composts on greenhouse gas emissions and forage maize yields

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## ABSTRACT

To develop agricultural practices that increase the soil carbon stock, we applied biochar in combination with manure compost (MC), a conventional organic amendment, and evaluated greenhouse gas (GHG) emissions and forage maize yields. Five treatments were established: (1) no-nitrogen control (P+K only), (2) inorganic fertilizer (F) treatment, (3) biochar (B) + F (B+F) treatment, (4) MC+F treatment, and (5) B+MC+F treatment. Inorganic fertilizer was applied at 19 g N $m^{-2}$, 8 g P $m^{-2}$, and 11 g K $m^{-2}$ in all treatments except the control (no N) and the MC+F and B+MC+F treatments (no added K owing to sufficient K in MC). MC (3.58% ± 0.26% N, 35.5% ± 2.8% C on dry matter [DM] basis, mainly cattle manure) was applied at 1000 g DM $m^{-2}$ in the MC+F and B+MC+F treatments. Biochar (80.2% ± 3.9% C on DM basis, made mainly from wood, with particle size of <5 mm) was applied at 1000 g DM $m^{-2}$ in the B+F treatment, and 10% by weight (289–306 g DM $m^{-2}$) of MC in the B+MC+F treatment. Three blocks were prepared, and five treatment plots (8 m × 6 m = 48 $m^2$ per plot) were randomly arranged within each block (total of 15 plots) in an experimental field at our research center in Sapporo, Japan. The field soil is classified as Allophanic Andosols. GHGs ($N_2O$, $CH_4$, and $CO_2$) were measured at least weekly, except during the snow season, in each plot by the closed chamber method. For $CO_2$ measurement, to exclude the influence of root respiration, stainless steel plates were inserted into the soil around the chamber base to a depth of 30 cm. Forage maize (*Zea mays* L.) was grown (in 75-cm rows and an 18-cm plant spacing) in each plot. Experiments were conducted from 1 May 2023 to 24 Apr 2024 and from 1 May 2024 to 24 Apr 2025. The GHG balance (total GHG emissions as $CO_2$ equivalent minus input C from biochar, MC, and crop residues) in each treatment decreased in the order of control ≥ F > MC+F > B+MC+F > B+F in each year (Fig. 1). It was positive in the control and F treatments, slightly negative (close to 0) in the MC+F treatment, and negative in the B+MC+F and B+F treatments. The addition of biochar did not affect GHG ($N_2O$, $CH_4$, and $CO_2$) emissions. Forage maize yields did not differ significantly among treatments in 2023–24 except in the control, in which it was significantly lower. But the yield was significantly higher in the B+MC+F treatment than in the other treatments in 2024–25, and yields tended to be higher in the treatments with MC. The addition of biochar to MC increased the soil C stock and had no effect on or increased forage maize yield relative to MC alone.

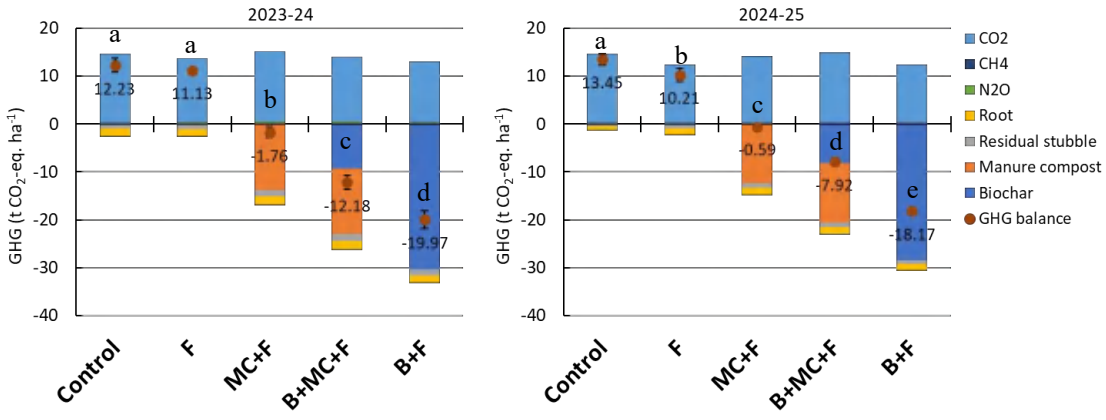



Figure 1 GHG balance in the field experiments in 2 years. Identical letters indicate that there is no significant difference among GHG balance by Tukey's HSD test ($P < 0.05$).

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# Determining acid neutralization capacity of crushed basalt during enhanced rock weathering in soil

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## ABSTRACT

Enhanced rock weathering (ERW) is a promising carbon dioxide ($CO_2$) removal strategy achieved through application of crushed silicate rock to soils. Beyond its potential for large-scale atmospheric $CO_2$ drawdown, ERW may provide agricultural co-benefits such as soil pH enhancement, replenishment of soils with essential macro and micro-nutrients, stabilization of soil organic carbon, and increased crop yields. While agriculture offers an infrastructure for ERW, the weathering rates of applied minerals and their impacts on soil and plant systems remain unclear. Among various silicate lithologies, basalt, a Ca- and Mg- rich mafic rock, is suitable for ERW due to its favorable mineralogy, high weathering rate, and widespread availability as a reasonably fine grained (<4 mm) quarry by-product. This study characterizes the physical and chemical properties of three different basalts from South Australia, Queensland, and New South Wales, Australia to evaluate their liming value in acidic agricultural soils. The study focused on the weathering rate, base cation release, and acid neutralization capacity (ANC) of basalt, which holds potential as an alternative to agricultural lime for correcting soil acidity. The particle size distribution of basalt was determined by sieving followed by laser diffraction (<75 µm fractions) analysis and, specific surface area (SSA) was measured using the $N_2$ adsorption-desorption method. Surface morphology and roughness were evaluated using scanning electron microscopy (SEM). Mineralogy and elemental compositions were determined through X-ray diffraction (XRD) and SEM with energy dispersive X-ray spectroscopy (SEM-EDS), and total elemental contents were analyzed using inductively coupled plasma-optical emission spectroscopy and mass spectrometry (ICP-OES/MS). The basalt samples yielded p80 values (i.e., 80% of particles less than this size) of 1,454-1,710 µm. Elemental analysis across all basalt samples indicated high concentrations of the essential plant macro-nutrients such as Ca (56.33-73.30 g/kg), Mg (34.78-49.77 g/kg), K (16.84-26.36 g/kg), P (0.40-5.70 g/kg) and, S (0.17-0.26 g/kg). Potentially toxic elements such as As and Cd, were present at 0.86-2.75 g/kg and 0.08-0.35 g/kg, respectively. The ANC values of basalt samples will be determined by titrations and a 90-day soil incubation experiment, comparing five treatments: T1 (<75 µm basalt), T2 (<75-250 µm basalt), T3 (<250-4000 µm basalt), T4 (pure $CaCO_3$), and T5 (agricultural lime). The findings of this study will provide valuable insights into the industrial relevance of utilizing basalt as an alternative soil amendment enhancing fertility, crop production, and atmospheric $CO_2$ removal via minimizing risks of potentially toxic element release.

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# Greenhouse gas emissions as influenced by integrated conservation management practices under organic production in a sandy soil

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**ABSTRACT**

Organic agriculture is a prominent strategy for maintaining or enhancing sustainability; however, the impacts of common conservation management practices within these systems remain underrepresented in the scientific literature. Here, a two-year field experiment was established to assess the integrated effects of cover cropping (cereal rye and hairy vetch mixture), manure compost amendment (with and without), and tillage practices (no-till and conventional tillage) on soil biogeochemical properties, greenhouse gas emissions ($CO_2$, $CH_4$, and $N_2O$), and yields in a sandy soils under organic vegetable production (tomato-sweet corn) from 2022 to 2024. Integrating the CC mixture resulted in higher $CO_2$ emissions, likely due to increased organic C inputs from root exudates and residue returns, which, however, were not affected by the simultaneous applications of manure compost and conventional tillage. No significant treatment effects on $CH_4$ and $N_2O$ emissions or vegetable yields were observed throughout the study. Conservation tillage with fall manure application and CC mix resulted in a higher greenhouse gas index (GHGI) than fallow, which was attributed to higher GHG emissions under CC and a similar vegetable yield among all treatments. Overall, integrated conservation management practices did not result in significantly higher environmental footprints and could serve as promising options for sustainability and soil conservation.

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# Can Perennials Cut Nitrous Oxide Emissions? Insights from Manitoba Cropping Systems

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**ABSTRACT**

Agriculture is a major source of greenhouse gas (GHG) emissions. Nitrous oxide ($N_2O$) is especially important because it has a strong warming effect and stays in the atmosphere for a long time. Reducing $N_2O$ from farmland is a key step toward the net-zero climate goals. As part of the Leveraging Ecosystems to transform Agriculture on the Prairies (LEAP) project, this study examines how different cropping systems and soil textures affect $N_2O$ emissions in Manitoba, Canada. The cropping systems include perennial, annual, and intermediate systems. Two main soil textures are studied: clay and sandy. These systems represent common farm practices in the region.

This is a three-year (2025-2027) field study across six sites. During the growing season, in-situ $N_2O$ fluxes are measured using static chambers. At the same time, silicon diffusive samplers collect $N_2O$ concentrations at 5, 15, 30, and 60 cm soil depths. These measurements help us understand both surface emissions and $N_2O$ movement and production below ground. The study addresses three main questions:
(1) Do perennial systems release less $N_2O$ than annual or intermediate systems?
(2) How does soil texture change $N_2O$ emissions and productions?
(3) What soil, environmental, and management factors mainly control $N_2O$ emissions?

We expect that perennial systems may lower emissions because they receive less fertilizer, disturb soil less, keep living roots year-round, and improve soil structure. Soil texture may also influence $N_2O$ production and emissions by affecting soil water, aeration, and microbial activity. The results will give new information about how farm management and soil conditions affect $N_2O$ emissions. This knowledge can support better nutrient management and help design farming systems that ensure crop production while reducing GHG emissions. Preliminary findings from the first year of field measurements will be shared in this poster.

# A Spatially-Explicit Framework for Agricultural Best Management Practices: Guidelines, Database, and Future Directions

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**ABSTRACT**

The effective implementation of Best Management Practices (BMPs) is crucial for mitigating the environmental impact of agriculture. However, the vast and often disorganized nature of existing BMP information can hinder their adoption and optimization. This initiative addresses this gap by introducing a comprehensive program to establish clear guidelines, a centralized database, and a robust conceptual framework for agricultural BMPs. A key innovation of our approach is the spatial categorization of all BMPs into four distinct categories: Edge-of-Field Practices, Airway BMPs, Surface BMPs, and Underground BMPs. This spatial taxonomy provides a systematic method for understanding, selecting, and implementing practices based on their location and primary zone of influence within the agricultural landscape. The outcomes of this initiative include: (1) a set of refined BMP guidelines tailored to this new categorization, (2) a searchable database to facilitate access to technical specifications and efficacy data, and (3) a conceptual framework that supports decision-making for farmers, planners, and policymakers. Finally, we discuss the future direction of this initiative, including the integration of precision agriculture technologies and the development of decision-support tools, aiming to enhance the scalability, effectiveness, and adoption of conservation practices for sustainable agricultural systems.

# Mechanism of soil carbon sequestration in cover cropping systems

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**ABSTRACT**

Cover cropping is an effective agricultural management practice to enhance soil organic carbon (SOC) sequestration and mitigate climate change. However, the contributions of different cover crop (CC) species to specific soil carbon (C) fractions remain unclear. Here, we combined a 5-year summer CC-winter wheat field experiment and an in-situ $^{13}$C-labeled CC residue decomposition experiment on the Loess Plateau of China to clarify: (1) the responses of soil C fractions to cover cropping, and (2) the distribution and sequestration mechanisms of CC-derived C. In the field experiment, three CC treatments were established during summer fallow—soybean (*Glycine max* L., SB), sudangrass (*Sorghum sudanense* (Piper) Stapf, SG), and their mixture (SS)—with residues incorporated into the soil two weeks before winter wheat planting annually. The in-situ decomposition experiment included $^{13}$C-labeled SB residues, $^{13}$C-labeled SG residues, and a no-residue control to investigate CC residue decomposition dynamics, the distribution of CC-derived C into aggregate-protected and unprotected fractions, and associated sequestration mechanisms. Measured soil C fractions included coarse particulate organic C (cPOC), free fine particulate organic C (fPOC), intra-microaggregate fine particulate organic C (iPOC), and mineral-associated organic C (MOC), with iPOC and MOC considered protected against mineralization. Field experiment results showed that integrating CCs into the winter wheat system enhanced soil aggregation and SOC sequestration compared to no cover cropping, primarily by increasing microaggregate-protected C and MOC and thus improving C stabilization. The SS mixture was more effective than monoculture SB or SG in promoting aggregate stability and C fractions. In-situ incubation results indicated that the seasonal cumulative recovery rate of CC-derived C in SOC was higher for SB than SG. Soil C sequestration from CC residues occurred mainly as aggregate-protected C, predominantly MOC. Cover cropping directly promoted SOC sequestration primarily by increasing aggregate-protected C. SG residue incorporation sequestered C mainly via enhancing cPOC and iPOC, while SB residue increased cPOC, iPOC, and MOC. Collectively, our findings clarified the distinct C sequestration mechanisms of legume and non-legume cover cropping systems, providing scientific supports for CC adoption in climate-smart agriculture in the Loess Plateau and similar regions.

**Acknowledgments**

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# Adopting wheat-legume intercropping enhances crop productivity and soil quality: Evidence from living labs across Pakistan under LEGUMINOSE Project

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**ABSTRACT**

Cereal-legume intercropping provides multiple benefits to agroecosystems, and thus, can promote sustainable intensification and climate-resiliency. However, such agricultural practices are little explored in dryland agroecosystems such as those existing in Pakistan. As a part of the Horizon Europe LEGUMINOSE Project, we established 14 wheat-legume intercropping living labs at farmers' fields (eight wheat-pea, five wheat-chickpea and one wheat-faba bean) across Pakistan. Thirteen living labs followed strip intercropping method whereases alternative row intercropping method was adopted at one wheat-pea intercropping lab. At the end of the growth season, crops were harvested to record biomass and grain yield data; surface soil samples were collected for analysis of soil physico-chemical and biochemical functions. We also collected economic analysis and farm-profitability data from one wheat-pea living lab. Results revealed synergistic effects of cereal-legume intercropping mainly on the biomass and yield of wheat; wheat biomass production and grain yield were higher when intercropped with legumes than solo cultivated wheat. Similar trends were observed for wheat-pea and wheat-chickpea intercropping living labs; however, under the wheat-faba bean living lab, both the yields of wheat and faba bean were lower under intercropping compared to their solo cultivations. When wheat and pea were intercropped following the alternative row method, this also did not increase biomass and grain yield of wheat and peas under intercropping. Data on land equivalent ratio (LER) also suggested cereal-legume intercropping resulted in more productivity as LER values were generally >1.00 in most cases. Economic analysis from one wheat-pea intercropping living lab showed adopting intercropping was more profitable and also resulted in better grain quality. Results from soil nutrient availability and soil organic carbon (SOC) analyses provided evidence that cereal-legume intercropping improved soil fertility and quality. These living lab studies demonstrated that cereal-legume intercropping can be an important tool to increase crop productivity and soil multifunctionality.

**Acknowledgments**

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# Towards a low-carbon and climate-resilient Mediterranean agriculture: the integration of Conservation Agriculture and 4R Nutrient Stewardship in herbaceous and woody crops

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**ABSTRACT**

Conservation Agriculture (CA) and 4R Nutrient Stewardship are two pillars to adapt to climate change, enabling productive, climate-resilient and low-carbon agricultural systems. CA promotes permanent soil cover, minimum soil disturbance and crop diversification, enhancing soil organic matter (SOM), water infiltration, biodiversity and reducing erosion and greenhouse gas (GHG) emissions. In combination with the 4R principles (right source, rate, time and placement of fertilizers), nutrient use efficiency can be maximized while minimizing losses of nitrogen (N) and phosphorus (P). However, evidence under real farm conditions, especially in Mediterranean environments where carbonates pose a major nutrient constraint and SOM content is commonly low, remains limited. Therefore, the aims of this study are: i) to evaluate whether localized, variable-rate applications of single P fertilizers at sowing, together with delayed or crop-specific N applications, improve nutrient use efficiency, and reduce GHG emissions; ii) to assess the role of legumes and cover crops in increasing SOM, fixing biological N, and improving water balance under Mediterranean rainfed conditions, and iii) to quantify CA impact on carbon (C) sequestration, lower $CO_2$/$N_2O$ emissions and reduced fuel use relative to conventional tillage systems. To this end, four field trials in four long-term commercial farms under CA are developed: two for annual crops (cereals, sunflower and legumes in crop rotation), and two for perennial crops (olive and citrus orchards). The experimental design in each field follows a complete randomized block design with four different treatments: i) conventional tillage and conventional fertilization, ii) CA and conventional fertilization, iii) CA and optimized fertilization (following the 4R principles), and iv) CA with strategically managed groundcovers or cover crops. In annual rotations, focus is on direct seeding and variable-rate P placement, while in olive and citrus orchards groundcovers are used to improve SOM, nutrient cycling and biological N fixation. Under this combined framework, GHG emissions ($CO_2$ and $N_2O$) together with several soil-health indicators such as enzyme activity and C sequestration are being periodically measured to generate robust, transferable data to support the transition toward a low-carbon, resource-efficient agriculture. In this sense, optimized fertilization improves nutrient use efficiency and lower GHG emissions, while cover crop mixtures enhance soil functionality even under the limited precipitation typical of Mediterranean conditions, fully aligning with European and Mediterranean sustainability targets.

**Acknowledgments**

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# Enhancing Soil Resilience and Climate Adaptation through Site-Specific Agroecological Strategies - AGROSUS Project

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## ABSTRACT

Achieving Climate-Smart Agriculture (CSA) requires Best Management Practices (BMPs) that not only ensure productivity but also enhance soil resilience and mitigation potential against climate variability. Within the framework of the Horizon Europe project AGROSUS (GAP-101084084), this study assesses the impact of agroecological (AGRO) weed management strategies versus conventional chemical control (CON) on soil health indicators across six distinct European biogeographical regions: Alpine (ALP), Atlantic (ATL), Boreal (BOR), Continental (CONT), Macaronesian (MAC), and Steppic (STP). Soil samples from long-term field trials were analyzed for physicochemical properties using multivariate statistical approaches. Results revealed that while regional pedogenesis explained over 50% of the total variance, AGRO induced significant, site-specific alterations. In CONT region, soils exhibited the highest sensitivity, with AGRO significantly improving drought adaptation indicators, increasing field capacity water content ($p < 0.05$). The BOR and STP regions demonstrated significant increases in Cation Exchange Capacity (BOR) (8.17 (AGRO) vs 6.25 $cmol^+ kg^{-1}$ (CON), $p < 0.001$) and STP (22.7 AGRO vs 18.13 $cmol^+ kg^{-1}$ (CON); and exchangeable Calcium (BOR: 1339.89 (AGRO) vs 966.09 (CON) mg $kg^{-1}$) (STP: 3940.25 (AGRO) vs 3264.91 (CON) mg $kg^{-1}$) ($p<0.001$) under agroecological management. under agroecological management. This enhancement in soil structure is directly linked to improved soil organic carbon stabilization, a key pillar of climate mitigation. Similarly, the Alpine region showed tightened nutrient cycling, marked by significantly different Nitrate levels (7.15 (AGRO) vs 9.72 (CON) mg $kg^{-1}$, $p = 0.006$). In the saline-prone Macaronesian region, sustainable practices moderate Electrical Conductivity (152.98 (AGRO) vs 232.25 $dSm^{-1}$ (CON), $p = 0.016$), suggesting a vital pathway to mitigate salinization. Conversely, the Atlantic region displayed physicochemical stability with minimal significant changes, suggesting CSA strategies here should focus on biological indicators. This data provides a robust framework for tailoring agroecological strategies within the AGROSUS project, supporting the transition towards resilient agroecosystems across Europe in alignment with the EU Farm to Fork Strategy and the European Green Deal.

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# Nitrogen use for improved profitability and sustainability of rice production in central Myanmar

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## ABSTRACT

This study explores optimal N application rates for sustainable rice production in central Myanmar by integrating recent research with additional economic and environmental analyses. Results indicate limited yield responses to applied N in monsoon rice, but significant gains—from ~4 to 8 t ha_1—are achievable in dry-season irrigated rice mainly due to higher solar radiation during the dry season. For monsoon-season rice, the economically optimal N rates were found to be 82.8 kg N ha–1 with the maximum net economic benefit (NEB) at 617 US$ ha_1. For dry- season irrigated rice, higher N rates were recommended, with the economically optimal N rates at 202 kg N ha–1 and the maximum NEB at 661 US$ ha_1. However, high fertilizer N inputs to rice in Myanmar have been shown to increase native soil N extraction in rice paddies and negatively affect microbial N retention and the promotion of Nr losses. If we take the social costs of Nr losses into the cost benefit analysis, the ecological optimal N rates were found to be 66 kg N ha_1 for monsoon season rice and 48.2 kg N ha_1 for dry-season irrigated rice. The adoption of ecologically optimal N rates could avoid social pollution costs of US$55 and US$368 per hectare annually compared to the current farming practices and economically optimal N rates, with benefits that outweigh the marginal drop in net economic returns. Farmer engagement revealed a pReferences for co-developing tailored fertilizer strategies with peers, extension agents, and researchers via interactive platforms (e.g., Facebook). This participatory model may be extended to similar contexts in Cambodia and Lao PDR.

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# Sustainable Pathways for Southeast Asia's Rice Systems

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**ABSTRACT**

Rice production in Southeast Asia is critical to local food security and rural livelihoods, providing over half of daily caloric intake and contributing more than one-third of household income. However, existing research is unevenly distributed across the region. Much of the current evidence base draws on relatively well studied countries such as Thailand, while nations like Lao PDR, Vietnam and Cambodia remain under presented in the literature. Their rice sectors are characterised by low external inputs, and large reliance on rainfed production. Although these features are often framed as limitations, they also represent a unique opportunity. Unlike China and India, where decades of intensive nutrient use have generated severe environmental impacts, these less managed systems are still a stage where sustainable intensification can be achieved without inheriting the environmental legacy of overuse.

This review synthesises current knowledge on rice production in underdeveloped regions in Southeast Asia, highlighting the environmental and socioeconomic factors shaping production. It argues that improving soil fertility through site-specific nutrient management, integrating organic inputs, and adopting water-saving approaches such as alternate wetting and drying can substantially enhance productivity while maintaining low environmental pressure. Coupling these agronomic interventions with modelling tools (e.g. ORYZA, CERES-Rice) enables more accurate and cost-effective planning under increasing climate variability. Policy measures that reward ecosystem services and recognise the added value of green rice products can create additional income streams for smallholders, supporting both livelihood improvement and the transition towards sustainable management.

Together, these strategies illustrate a development pathway in which Southeast Asia's less-intensive rice systems can leapfrog the high-pollution trajectory experienced elsewhere, advancing productivity, nitrogen-use efficiency and long-term resilience through a greener model of rice production.

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# Functional legume rotations optimize global synergies between soil organic carbon accrual and crop yield

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## ABSTRACT

Functional legume rotations offer a promising pathway for improving soil health while sustaining food production under climate change. Soil organic carbon (SOC) is central of this challenge[1], yet the global capacity of legume functional types (grain, forage, green manure) to enhance SOC and yield—and their future climate sensitivity—remains poorly quantified. Existing evidence shows inconsistent SOC responses and unclear yield synergies[2], limiting targeted soil-restorative cropping strategies.

Here, we compile the most comprehensive global synthesis to date, integrating 161 legume rotation systems across 610 sites with 3,865 SOC and 15,282 yield observations from 1959 to 2024. Using machine learning upscaling (random forest; $R^2$ = 0.73–0.86) and spatial prioritization, we quantify: (i) the SOC and yield impacts of legume types, (ii) global biogeographic patterns, and (iii) performance under future climates (SSP245, SSP585).

Across systems, legume rotations increased SOC and crop productivity by 4.4% and 20%, respectively. Functional type was the dominant determinant of SOC gains: Forage legumes increased SOC by 8.2%, green manure by 5.2%, whereas grain legumes showed minimal change. Carbon gains coupled with yield benefits, with green manure rotations producing the largest yield improvement (35.3%) and the strongest SOC–yield synergies. Spatial upscaling revealed marked biogeographic differentiation: Forage performed best in temperate humid regions, while green manure was most effective in C-poor tropical and subtropical croplands. Optimized global legume allocation could deliver up to 8.6% SOC sequestration and 43.5% yield increase, with balanced SOC–yield maximization achieving 7.1% and 41.3%, respectively. Future climate projections indicate that SOC–yield co-benefits will strengthen under SSP585 by 5.6–8.5% by 2100, but ~40% of croplands need optimal legume types shifts to maintain benefits. Green manure showed the highest climatic resilience, requiring substantially smaller geographic adjustments. Our findings demonstrate that functional diversification of legume rotations is a globally scalable strategy for enhancing SOC while supporting food security. By linking legume functional types to geographic context and climate adaptability, this study provides a quantitative framework to inform soil-centered climate-smart agricultural cropping worldwide.

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# Influence of soil pH and cover crop residues on the abundance of ammonia oxidizing microorganisms and nitrous oxide emissions in tropical agriculture soils

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## ABSTRACT

The increasing urgency of climate change mitigation requires a better understanding of the trade-offs between soil organic carbon (SOC) sequestration and nitrous oxide ($N_2O$) emissions. While cover crops are integral to no-till systems and enhance SOC storage, they also influence nitrogen (N) cycling, potentially increasing $N_2O$ emissions that can offset their climate benefits. This study investigated how different N sources, organic (legume and grass cover crop residues) and inorganic (ammonium sulfate), affect ammonia-oxidizing microorganisms and $N_2O$ emissions in tropical soils with contrasting pH (5.6 and 7.0) during a microcosm incubations experiment. Legume residues mineralized approximately 20 µg NH4+-N g-1 more than grass residues in acidic soil, and both residues increased soil pH by up to 1.5 units within 10 days. Nitrous oxide emissions varied significantly with N source and soil pH, exhibiting distinct temporal patterns. In acidic soil, litter decomposition produced higher $N_2O$ emissions than ammonium sulfate during the first 13 days, although cumulative emissions were 45% greater than with litter. In near-neutral pH soil, ammonium sulfate and legume residues generated up to 10.7-fold higher $N_2O$ emissions than grass residues or the control. Emission factors showed that ammonium sulfate contributed a greater proportion of added N to $N_2O$ emissions, particularly in acidic soil (0.48% of total N), whereas grass and legume residues emitted 0.13% of their total N, corresponding to 0.54 and 0.44% of mineralized N, respectively. In near-neutral soil, EFs decreased to 0.32% for ammonium sulfate and to 0.05 and 0.11% of total N (0.21 and 0.54% of mineralized N) for grass and legume residues. The abundance of ammonia-oxidizing bacteria increased under all N amendments relative to the control, especially in acidic soils with organic inputs, whereas ammonia-oxidizing archaea were most responsive to organic inputs in near-neutral soils. Cover crop management play an important role in regulating soil N dynamics and activity of ammonia-oxidizers by modifying soil pH and ammonium availability, thereby influencing $N_2O$ emissions and partially offsetting the climate benefits of SOC sequestration.

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# Effects of Plant Density, Nitrogen Rate and Supplemental Irrigation on Maize Source-Sink Relationship and Water-Nitrogen Use Efficiency Under Straw Mulch in Northeast China

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## ABSTRACT

Although the effects of planting density, nitrogen fertilizer application, and supplemental irrigation on crop growth are well-studied, their underlying mechanisms, particularly source-sink relationships, in yield formation and water/nitrogen use efficiency improvements remain unclear. This study investigated how these three factors affect source-sink characteristics in maize, aiming to identify key factors for improving yield and resource use efficiency. The goal is to support a green theoretical system for crop that achieves high yield, high efficiency, and synergy. For this purpose, a three-year field experiment was conducted during the maize growing seasons from 2023 to 2025, with treatments combining different planting densities, nitrogen application rates, and supplemental irrigation volumes. Source and sink indicators were measured throughout the growth period, and their relationships were quantified. Results showed that leaf area index (LAI) increased with planting density and irrigation under the same nitrogen level. Higher nitrogen application led to higher and longer-lasting relative chlorophyll content (SPAD) peaks. Biomass under medium and high nitrogen treatments was significantly greater than that under the low nitrogen treatment. Split nitrogen application enhanced maize yield. However, yield gains from higher density diminished beyond the D2 level. Total source supply and source supply rate increased with planting density under the same nitrogen input. Under the different cultivation practices, sufficient source supply was accompanied by a concurrent increase in sink storage capacity. The source-sink ratio was >1 in most treatments, indicating ample source for sink development. Compared to one-time basal fertilization, integrated water-fertilizer topdressing significantly increased partial factor productivity of nitrogen ($PFP_N$) and nitrogen use efficiency (NUE), by up to 209.49%. Source serves as the key link connecting planting management and resource use efficiency. Planting density was the main driver of source improvement. Optimal density and precise water-nitrogen synchronize source and sink, enhancing both yield and water/nitrogen use efficiency. This study provides new insights into source-sink regulation under density-nitrogen-irrigation interaction and provides a physiological pathway for high-yield, high-efficiency maize cultivation.

**Key words:**Planting density, Nitrogen rate, Supplemental irrigation, Source-sink relationship, Water-nitrogen use efficiency

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# Effects of manure and agronomic practices on particulate, dissolved, and mineral-associated organic matter in a long-term integrated crop-livestock system

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## ABSTRACT

Emerging soil organic matter (SOM) continuum models describe SOM as a spectrum linking particulate, dissolved, and mineral-associated organic matter. At the scale of soil aggregates, dissolved organic matter (DOM) serves as a dynamic and mobile link within the SOM continuum, yet the agronomic factors regulating aggregate-scale DOM remain poorly understood. We used soil aggregates from a long-term integrated crop-livestock experiment in Southern Manitoba, Canada (est. 2007) with an RCBD split-split plot design: two cropping systems (annual vs annual-perennial), four manure treatments (no manure, liquid pig, solid pig, solid dairy), and two soil management strategies (regenerative: no-till with cover crops; vs conventional tillage). Bulk soil aggregates (< 8 mm) were wet sieved into macroaggregates (250-2000 µm), microaggregates (53-250 µm), and silt+clay (< 53 µm). Macro- and microaggregates were water-extracted to obtain aggregate-derived DOM and further fractionated to isolate associated particulate (POM) and mineral-associated (MAOM) fractions. DOM was characterized using UV-Vis indices and fluorescence EEM-PARAFAC components. We used PERMANOVA ($\alpha = 0.05$) to test treatment effects, NMDS to visualize DOM gradients, and envfit to link those gradients to POM and MAOM mass fractions and C: N ratios. Manure form was the dominant driver of DOM composition, whereas crop rotation and soil management had negligible effects. NMDS revealed an aggregate-DOM continuum in which DOM shifted from more plant-like, aromatic signatures toward more N-rich, microbially processed components, and these gradients closely tracked underlying POM and MAOM quantity and stoichiometry. Solid manures, especially solid pig, most strongly diversified this DOM continuum by enhancing both plant-derived and microbially processed fluorescence components within aggregates. Preliminary $\delta^{13}C$–$\delta^{15}N$ biplots for macroaggregate-associated cPOM and free MAOM show that solid pig treatment occupies the most $^{15}N$-enriched region of C–N space, indicating efficient transfer and incorporation of manure-derived N into both particulate and mineral-associated pools.

# Soil Organic Carbon Buffers Wheat Yield Against Warming by Regulating Phenological Sensitivity

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## ABSTRACT

**Background:** Global warming threatens crop production primarily by accelerating crop development, shortening phenological phases, and reducing the time available for biomass and yield formation. Soil Organic Carbon (SOC), a key regulator of soil physical and biological functions, has been proposed to mitigate warming impacts through its effects on soil water-holding capacity and thermal dynamics. However, the quantitative capacity of SOC to buffer yield loss under warming, and whether its effects are mediated by modifying crop phenological responses to temperature, remain poorly quantified.

**Methods:** To address these gaps, we performed a meta-analysis of 9 field experiments with controlled temperature treatments from 13 site-years across China (growing-season temperatures ranging from 5.4 ℃ to 17.3 ℃, $n$ = 34). We quantified the interactive effects of SOC and temperature on wheat yield, and tested the hypothesis that SOC buffers yield against warming by altering crop phenological sensitivity to temperature.

**Results:** The study revealed a significant positive interaction between SOC and temperature on wheat yield. While elevated temperatures generally reduced yields, higher SOC levels significantly mitigated this loss. A critical SOC threshold of 16.3 g $kg^{-1}$ was identified, above which warming-induced yield loss was largely eliminated. Importantly, we found a strong negative correlation ($R=-0.776$, $P<0.01$) between SOC content and the developmental sensitivity of the vegetative stage to temperature. This indicates that SOC acts as a phenological stabilizer. High SOC soils effectively alleviated the negative effects of warming on crop's physiological development, slowing down the temperature-induced acceleration of development and extending the vegetative growth period, which benefit high yield.

**Conclusion:** Our findings advance understanding of soil-climate-crop interactions by identifying a novel mechanism: SOC buffers wheat yield against warming primarily through phenological stabilization. The critical threshold (16.3 g $kg^{-1}$) provides a practical target for SOC management in Chinese wheat fields to enhance climate resilience. Enhancing SOC sequestration therefor offers a synergistic pathway for climate smart agriculture by offsetting greenhouse gas emissions while reducing the harmful effects of high temperature on crop development.

**Keywords:** Soil Organic Carbon; Climate Warming; Wheat Yield; Phenological Stabilization; Crop Resilience

# Decadal biochar legacy alters soil physicochemical properties but not microbial C turnover

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**ABSTRACT**

Biochar is increasingly applied as a land-based carbon (C) sequestration option with agronomic co-benefits. However, the long-lasting effects of biochar in soil ecosystems remain poorly documented. In particular, it is unclear whether a single application leaves durable and decadal legacies, e.g., for microbial soil C cycling, and whether these effects depend on soil texture, and biochar application dose or biochar types. Here, we studied a semi-field lysimeter facility in Denmark where biochar was applied to investigate (i) effects of soil texture and biochar application dose with three soils (coarse sand, sandy clay, clay) that received a single straw biochar application in 2015 at doses of 0, 0.5, 1 and 2% (w/w), and (ii) effects of biochar type with a sandy clay soil that received a single application in 2015 of straw biochar, manure biochar and a 1:1 mix thereof, all at 1% (w/w). All treatments had biochar mixed into the top 0-20 cm of the soil and were established in four replicates. A decade later in 2025, we measured topsoil physicochemical properties and tested C turnover using $^{14}$C-labelled ryegrass root material and $^{14}$C-labelled vanillin in mesocosms to resolve potential changes in mineralization of organic C compounds with varying chemical recalcitrance and potential priming of native SOC. Across soil types, the single biochar application had decadal legacy effects in terms of increased soil C in an expected dose-dependent manner. Beyond total C, biochar raised water-holding capacity and decreased bulk density in a dose- and texture-dependent way. Effects on soil pH after 10 years were minor, as opposed to marked increases seen in the first year after biochar application. Basal respiration (measured as cumulative $CO_2$ evolution during 21 weeks) in each of the three soils showed no significant response to straw biochar across application doses (0.5, 1 and 2% w/w) whereas the mixture of straw and manure biochar (1% w/w) showed significantly higher $CO_2$ evolution than the other treatments (mix > control ≈ manure > straw). The substrate-induced respiration assays with added root materials or vanillin showed no significant differences in net respiratory response across the tested application doses or biochar types. Across all three soil textures, the priming effects induced by root addition remained similar regardless of biochar application dose throughout the incubation period. In the sandy clay with 1% biochar, biochar application regardless of the type lowered root-induced positive priming after incubation for 3 months. However, with extended incubation, such effect disappeared. In summary, our results show that biochar leaves long-lasting effects on soil physicochemical properties, while legacy effects on microbial turnover of C are relatively minor.

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# Root-zone Water and Salt Transport Dynamics and Irrigation Optimization in Mulched Drip-Irrigated Cotton Fields in Arid Regions

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## ABSTRACT

Under mulched drip irrigation in arid regions, soil water and salinity within the wetted root zone exhibit pronounced periodic transport driven by irrigation events. Crop water and salt stress is not only directly related to the magnitude of soil water content and salinity, but is also strongly coupled with the spatial distribution of the water-salt-root system and the dynamic physiological responses of crops to stress throughout the growing season. However, existing water-saving and salinity-control strategies primarily focus on soil water and salinity levels within the root zone-particularly in surface layers-while neglecting the synergistic effects of multiple interacting factors. As a result, irrigation regulation remains highly empirical, with limited precision, suboptimal water use efficiency, and an inability to formulate effective water-salt management strategies targeting specific yield objectives. To address these limitations, this study systematically integrates crop physiological responses to water and salt stress into an improved root water uptake model coupled with a soil water-salt transport model, substantially enhancing the simulation accuracy of soil water and salinity dynamics. Model parameters were calibrated and validated using field-measured soil water content and salinity data. The results indicate that the simulated soil water content achieved coefficients of determination ($R^2$) ranging from 0.65 to 0.73, with mean relative errors (MRE) of 0.05~0.08 $cm^3/cm^3$ and normalized root mean square errors (NRMSE) of 12.51%~25.36%. For soil salinity, $R^2$ values ranged from 0.65 to 0.73, with MRE of 0.57~0.98 g/kg and NRMSE of 17.28%~28.47%. These results demonstrate that the proposed model can reliably reproduce soil water and salt transport processes under mulched drip irrigation conditions. Using the validated model, soil water and salt transport dynamics were simulated under different combinations of irrigation quotas and irrigation water salinity. The results reveal that both irrigation quota and water salinity significantly affect the soil salinity change rate (RS), with irrigation quota exerting a more pronounced regulatory effect. Under the same salinity level, RS in the 0~40 cm soil layer decreased with increasing irrigation quota, whereas RS in the 40~80 cm layer exhibited a unimodal pattern, initially increasing and then decreasing. Higher irrigation water salinity increased the peak RS in the 0~40 cm layer; however, as irrigation quota increased, the RS increment induced by high salinity was progressively attenuated, indicating that larger irrigation quotas can effectively alleviate surface salt accumulation caused by saline irrigation. In contrast, RS in deeper soil layers (60~80 cm) responded weakly to irrigation water salinity, with only limited increases even under high salinity conditions, suggesting that salinity-induced accumulation in deep soil is substantially less pronounced than in upper and middle layers. Overall, this study provides critical scientific evidence for precision root-zone water-salt management and irrigation strategy optimization in mulched drip irrigation systems in arid regions.

**Key words:** Root-zone; Soil salinity dynamics; Irrigation; Model

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# Evaluating BMPs that reduce Greenhouse gas emissions ($N_2O$) and improve water quality: A case study in southern Ontario, Canada

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**ABSTRACT**

Agriculture is a primary nonpoint source of nutrient pollution, particularly phosphorus and nitrogen, leading to eutrophication and water-quality degradation in downstream ecosystems. While best management practices (BMPs) are widely promoted to reduce these loadings, their concurrent impacts on nutrient export and direct nitrous oxide ($N_2O$) emissions remain insufficiently understood, especially under cold climatic conditions.

Eleven agricultural best management practices (BMPs), including conservation tillage, fertilizer management, and cover cropping, were assessed in the cold-climate Speed River Basin (SRB) in southern Ontario using a revised Soil and Water Assessment Tool (SWATCCN2O). While BMPs successfully reduced sediment and phosphorus losses, their effects on nitrogen and nitrous oxide ($N_2O$) emissions varied, suggesting trade-offs between improving water quality and reducing greenhouse gas emissions. A multi-objective analysis identified strip tillage with banded fertilizer and red clover cover cropping after winter wheat as the most effective practices, forming an optimal BMP. The study showed that focusing on the top 20% of hydrological response units (HRUs) with the highest $N_2O$ emissions could reduce annual $N_2O$ by 16%. Increasing implementation across the remaining agricultural HRUs further reduced sediment, phosphorus, and nitrogen loadings by up to 17%, 80%, and 11.8%, respectively. These findings emphasize the need for integrated BMP strategies that deliver co-benefits for water quality and climate mitigation.

# Silvopastoral Systems as a Strategy to Increase Carbon Stocks and Improve Soil Health in Brazilian Drylands

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## ABSTRACT

Integrated agricultural production systems, such as Crop–Livestock–Forest Integration (ICLF), are nature-based solutions that represent a key strategy for sustainable agricultural intensification and climate change adaptation. ICLF systems are included in the Brazilian Sectoral Plan for Mitigation and Adaptation to Climate Change (ABC+ Plan), which supports the transition toward a low-carbon agricultural economy. To expand the evidence base on ICLF systems in Brazilian drylands, this study evaluated soil carbon and nitrogen stocks, as well as chemical, physical, and biological soil attributes, following the conversion of low-productivity pastures into silvopastoral systems in the Brazilian semi-arid region. The following land uses were assessed: native vegetation, low-productivity pasture, and two silvopastoral systems arranged with single-row and quadruple-row of *Eucalyptus urograndis* integrated with *Urochloa decumbens*. Soil bulk density, as well as carbon and nitrogen contents and stocks, were determined seven years after the implementation of the integrated systems. Additionally, microbial biomass carbon (C-mic), microbial quotient, the activity of β-glucosidase and arylsulfatase enzymes, and soil fertility parameters were evaluated during the dry and rainy seasons. Furthermore, the Soil Health Index was calculated using the Soil Management Assessment Framework (SMAF) tool. The conversion of low-productivity pastures to silvopastoral systems in Brazilian semi-arid region enhanced soil carbon stocks to a depth of 100 cm, with annual increases up to 4.81 Mg $ha^{-1}$. Improvements were also observed in chemical, physical, and biological soil attributes, with microbiological responses influenced by both management practices and seasonal climatic conditions. Overall, silvopastoral systems enhanced soil health indices derived from SMAF, demonstrating that integrated agricultural systems are a viable and effective strategy for restoring degraded soils and enhancing soil health in Brazilian drylands.

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# Including water-salinity stress hysteresis and compensation to empirical root water uptake models

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**ABSTRACT**

Root water uptake (RWU) is influenced not only by instantaneous soil conditions but also by two dynamic processes often neglected in models: stress hysteresis, arising from prior exposure to suboptimal water/salinity conditions, and compensation, where roots in zones with superior conditions offset uptake reductions in zones where soil is less conducive to RWU. Empirical RWU models, such as the Feddes model (FM), are widely used due to their simplicity and low data requirements, but typically neglect these dynamic effects.

Here, we extended FM by introducing a recovery coefficient to capture stress hysteresis and incorporating either a piecewise or continuous compensation function. Six models were tested: FM, single-process models - WM (hysteresis), PM (piecewise compensation), and DM (continuous compensation); and combined-process models - WM-PM and WM-DM. Using data from a greenhouse soil column experiment with winter wheat, we found that both historical stress and spatial heterogeneity in root zone water and salinity strongly influence RWU and transpiration by plants. The coupled models (WM-PM, WM-DM) outperformed FM and single-process models in simulating transpiration dynamics, improving $R^2$ by 10.1–12.9% for actual transpiration and 3.8–29.7% for relative transpiration, while reducing RMSE by 27.6–36.4% and 13.8–41.9%, respectively. The WM-DM showed the highest accuracy, attributed to its mechanistic incorporation of soil hydraulic conductivity, matric potential, and osmotic potential into the compensation function.

Numerical simulations further revealed distinct RWU distribution patterns among the models, particularly under water and salinity stress cycles. The selected WM-DM model, embedded into the one-dimensional Richards and convection-dispersion equations, successfully reproduced soil water and salinity dynamics in both the greenhouse soil column experiment and a two-year field study of a winter wheat–summer maize rotation ($R^2 \geq 0.86$, RMSE $\leq 0.0288$ cm$^3$ cm$^{-3}$ for water content, $R^2 \geq 0.66$, RMSE $\leq 0.40$ g kg$^{-1}$ for salinity). These findings highlight the value of explicitly accounting for both stress hysteresis and compensation in empirical RWU models, with implications for improved irrigation scheduling and salinity management.

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# Regional variation in the potential to reach net zero emissions in global agriculture

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**ABSTRACT**

Agriculture is a major contributor to global greenhouse gas (GHG) emissions. When associated land-use change is included, such as deforestation for pasture and croplands, peatland drainage, and loss of soil organic matter, emissions account for 20–25% of the global total anthropogenic GHG emissions, placing agriculture and land use together among the largest emitting sectors after energy and industry[1].

The dominant GHGs from agriculture are carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$). $CO_2$ fluxes arise largely from land-use change and soil management, including tillage, drainage of peatlands, and organic matter mineralization[2]. Livestock systems, especially ruminants, are the largest single source of $CH_4$, followed by flooded rice systems and manure management[3]. Croplands contribute significantly to $N_2O$ emissions through synthetic fertilizer use and manure incorporation into soils[4].

To reach climate neutrality by 2050, net zero GHG emissions are needed for all sectors. This is not feasible in agriculture since there are unavoidable losses of $N_2O$ and $CH_4$ which cannot fully be compensated by $CO_2$ sequestration but there is ample opportunity to reduce net GHG emissions by implementation of diverse, site-specific mitigation strategies. This includes: (i) enhancing soil carbon sequestration via cover crops, conservation tillage, organic amendments, and agroforestry; (ii) improving nitrogen-use efficiency through precision fertilization, inhibitors of nitrification and urease, and integrated crop–livestock systems; (iii) reducing $CH_4$ emissions through livestock dietary interventions, improved manure management, and alternate wetting and drying in rice systems; and (iv) avoiding and reversing high-emission land uses, such as peatland drainage and deforestation[5].

In this presentation we present the mitigation potential of agricultural emissions of $CO_2$, $N_2O$, and $CH_4$ at global scale, including where possible the spatial heterogeneity, as compared to current global $CO_2$, $N_2O$, and $CH_4$ emissions.

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# Optimizing soil improvement and nitrogen management for sustainable crop production

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**ABSTRACT**

Global food demand is projected to increase by 70% by 2050 (Cassman and Grassini, 2020). High-input agriculture meets this demand but causes nitrogen loss, greenhouse gas emissions and soil degradation, challenging alignment with UN Sustainable Development Goals. Soil quality, reflecting physical, chemical and biological traits, enhances crop yields, nutrient use efficiency and carbon storage. However, its quantitative relationship with nitrogen application and combined effects on productivity and emissions remain unclear globally. Existing nitrogen reduction strategies focus on short-term management, neglecting long-term soil enhancement. Using national field datasets (1981-2020) from China's rice ecosystems, combined with process-based models and life cycle assessments, we assess the impact of soil quality improvements on rice production under various nitrogen application rates. The results indicate that improving soil quality can lead to an average 9% increase in rice yield and a 6% reduction in yield-scaled carbon emissions. The northeast rice-growing regions in China, characterized by the highest soil quality and sustainability, can achieve sustainability targets primarily through optimizing nitrogen application rates. In contrast, the southern rice regions require a combined approach of soil improvement and nitrogen fertilizer optimization to achieve sustainable production. This study provides strategic insights into promoting sustainable rice production through targeted soil improvements and optimized nitrogen application.

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# Controlled-Release Fertilizers in BMPs for Sustainable Agriculture

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**ABSTRACT**

Controlled-release fertilizers (CRFs) become an important component of best management practices (BMPs) for sustainable agriculture. This fertilization technique can precisely supply nutrients to match crop needs, not only maximizing nutrient use efficiency but also mitigating non-point source pollution from agriculture. This presentation highlights recent advancement in CRF technologies, focusing on novel and ecofriendly coating materials for CRFs. Perspectives and future directions for integrating CRFs into BMPs to enhance the resilience and sustainability of agricultural systems are also discussed.

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# Comprehensive Review: Insights into the Dynamics of Soil Organic Carbon Stocks in Vineyards

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**ABSTRACT**

Vineyards are critical agroecosystems where intensive management often leads to soil degradation and a decline in soil organic carbon (SOC) stock. Maintaining plant cover is widely promoted as a sustainable practice to reverse this trend, yet its effectiveness varies significantly across different environments. This study aimed to quantify the impact of management, soil types and climate on SOC stocks in vineyards worldwide, and to unravel the complex interaction between these factors. Through global, meta-analysis of 188 soil profiles from 95 relevant articles we synthesized data covering 13 soil types, 9 climate classes and range of soil managements grouped into 5 categories, from bare soil to permanent plant cover. From heterogeneous reported data, SOC stocks were harmonized across five generic depth layers (0-20, 20-40, 40-60, 60-80, 80-100 cm). Statistical analyses were first performed on the entire profile to assess SOC stocks with respect to the three parameters individually. We then focused on the upper 20 cm to examine combined effects of factors (two at a time), concluding with a model incorporating all three parameters simultaneously to explain SOC stocks. Our results reveal that management practices (i.e. plant cover) are key for carbon storage, increasing SOC stocks from 40 % to 70 % when compared to conventional bare soil management. However, the efficacy of this practice is highly context dependent. The most substantial SOC stocks gains are observed when plant cover is applied to in responsive soil and under favourable climate. For instance, plant cover increases SOC stock by a factor of 3 to 4 in Cambisol under temperate climates. Conversely, the plant cover benefit is negligible in soils under hot Mediterranean climates where climatic constraints overrode the management efforts. These findings underscore that maximizing soil carbon storage in vineyards requires moving beyond broad recommendations to tailored, climate-smart strategies. The most effective approaches will be those that account for synergistic interactions between soil type and climate, ensuring that management practices are adapted to the specific context of each vineyard.

**Keywords:** Soil Organic Carbon (SOC), Soil health, Vineyards, Carbon Storage, Soil Management, Cover Crops

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# Optimal Selection of Soil Organic Carbon Prediction Models and Their Implications for Potential Soil Erosion Estimation Using the Revised Universal Soil Loss Equation in Southern Chinese Counties

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**ABSTRACT**

Soil erosion poses a significant threat to the agricultural productivity and ecological stability of counties in southern China. Accurately assessing potential soil erosion and identifying its key driving factors are crucial for formulating targeted soil and water conservation strategies. Taking the counties in southern China as the research area, this study employed the Revised Universal Soil Loss Equation (RUSLE) as the core analytical framework, with specific focus on three critical factors: K (Soil Erodibility Factor), R (Rainfall Erosivity Factor), and LS (Slope Length-Slope Steepness Factor). Given that soil organic carbon (SOC) constitutes a key variable in the calculation of the K factor, this study placed primary emphasis on SOC to address two core objectives: first, investigating how K factors—derived from SOC predicted by distinct models—influence the estimation of potential soil erosion; second, determining the optimal SOC prediction model. Three models were selected for SOC prediction, namely Random Forest (RF), Ordinary Kriging (OK), and Extreme Gradient Boosting (XGBoost), while Recursive Feature Elimination (RFE) was utilized to screen key feature variables. Additionally, explainable machine learning techniques were applied to quantify the relative importance of various factors affecting the K factor; this analysis indirectly revealed which factor exerts the most significant impact on potential soil erosion. Subsequently, the SOC prediction accuracy of the three models was compared using evaluation metrics, including the coefficient of determination ($R^2$) and root mean square error (RMSE), to identify the optimal SOC prediction model. The K factor was then calculated using the SOC results generated by this optimal model, and the derived K values were validated through comparison with existing published K factor datasets. Finally, the optimal K factor, in combination with precomputed R and LS factors, was integrated into the RUSLE model to estimate potential soil erosion in the study area. On this basis, the loss of soil organic carbon induced by soil erosion was further quantified. This study not only clarifies the performance of different SOC prediction models in supporting K factor calculation and soil erosion assessment but also identifies the dominant factors regulating soil erodibility and potential soil erosion. The findings provide a scientific basis for optimizing soil and water conservation strategies and safeguarding soil carbon pools in southern Chinese counties.

**[Key words]** Potential Soil Erosion; Soil Erodibility Factor; Explainable Machine Learning; Soil Organic Carbon Loss; Random Forest Model

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# Whole-profile soil organic carbon simulation in China using SOILcarb model

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**ABSTRACT**

The spatial distribution and turnover of soil organic carbon (SOC), a critical component of the global carbon cycle, remain highly uncertain. To address the limitations of conventional models, we used SOILcarb, a whole-profile (0–100 cm) SOC simulation framework for China. A key innovation of SOILcarb is its explicit representation of SOC dynamics using measurable carbon fractions—namely, particulate organic carbon (POC) and mineral-associated organic carbon (MAOC)—instead of traditional, empirically defined conceptual pools. This physically-grounded approach improves model interpretability and transferability. SOILcarb extends simulation from typical topsoil depths to the full 100 cm profile, capturing the distinct surface and subsurface processes that govern long-term carbon stabilization. We parameterized and validated the model using a comprehensive nationwide dataset of SOC, POC, and MAOC observations to 100 cm, alongside crucial soil and environmental data. The results show that SOILcarb successfully reproduces the observed spatial patterns and vertical dynamics of SOC across China. This framework advances our understanding of China's soil carbon storage and provides a robust tool for predicting its response to environmental change.

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# Coupled geomorphic and climate-driven biogeochemical processes regulate soil organic carbon stocks in agricultural terraces

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**ABSTRACT**

Agricultural terraces are among the most widespread human–made landforms. They profoundly reshape soil landscapes and influence the carbon cycle, yet the extent and drivers of their impact remain highly uncertain. By integrating field observations from 14 well-drained terrace landforms across a climatic–geochemical gradient with a data synthesis, we show that changes in soil organic carbon (SOC) stocks after terracing are governed by two coupled C turnover–geomorphic processes: replacement of lost topsoil C at eroding positions and stabilization of buried SOC at depositional positions. Climate strongly modulates these processes by shaping soil geochemistry and plant productivity, which in turn control SOC replacement and stabilization within terraces. Thus, terracing effects on SOC stocks shift from consistently positive in humid regions to mixed (positive and negative) outcomes in dry regions. This study establishes a framework for elucidating SOC dynamics in well-drained terrace systems and provides a scientific basis for targeted management strategies to enhance C sequestration in agricultural terraces globally.

**Acknowledgments**

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# Modelling climate change impacts on soil organic carbon dynamics in dryland croplands

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## ABSTRACT

The impact of climate change on soil organic carbon (SOC) remains uncertain, particularly in dryland agroecosystems where soils are inherently low in organic matter. Over recent decades, SOC has been repeatedly highlighted as a key parameter for maintaining soil functions and mitigating climate change through the sequestration of atmospheric carbon. In dryland croplands, SOC accumulation is also critical for maintaining crop productivity due to its influence on soil structure and, consequently, on soil water conservation. Under these conditions, certain management practices have been identified for their positive effect on SOC build-up. However, the behaviour of these practices under changing climate conditions is still poorly understood. In this context, the general aim of this study was to assess the effects of climate change on SOC dynamics in dryland croplands. To achieve this, the Daycent ecosystem model was first parameterized and validated using data from a long-term tillage and fertilization experiment conducted under rainfed Mediterranean conditions. Subsequently, eleven climate models and four CMIP6: SSP1-2.6; SS2-4.5; SSP3-7.0; and SSP5-8.5 were used to run the Daycent model under four management scenarios: conventional tillage and mineral N fertilization (CT-Nmin); no-tillage and mineral N fertilization (NT-Nmin); conventional tillage and organic fertilization (CT-Norg); and no-tillage and organic fertilization (NT-Norg). The Daycent model was run for 85 years (2015-2100 period) to estimate SOC and crop yield changes under each combination of management, climate scenario and climate model, both with and without the effect of rising atmospheric $CO_2$ concentration. In total, 440 simulations were performed.

The Daycent model predicted a marked effect of both management and climate scenarios on SOC changes. A large degree of heterogeneity was observed among the trends, depending on the climate model used. Despite this variability, the model predicted that most scenario-model combinations resulted in a carbon (C) sink situation, with SOC increasing over the 85-year period. Simulations without atmospheric $CO_2$ increase showed a lower sink C capacity compared with those that included rising $CO_2$ concentrations. In particular, the CT-min management scenario, when simulated without atmospheric $CO_2$ increase, showed SOC losses in several scenario-model combinations, acting as a C source. Across most scenario-model combinations, management scenarios with organic fertilisation presented the highest C sink potential.

This modelling study contributed to improving our understanding of the effects of climate change on SOC dynamics in Mediterranean dryland conditions. The results demonstrated that, under warmer and drier conditions, the selection of appropriate management strategies will be essential to maximize soil C sequestration capacity in these systems.

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This research was funded by the European Union Soil Mission programme under grant agreement No. 101112942 (MARVIC project) and partially by the Spanish State Agency for Research (AEI) (Grant PID2021–126343OB-C31).

# Divergent drivers of soil organic carbon factions across global pedoclimatic zones

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**ABSTRACT**

Soils are central to the global carbon (C) cycle and represent a critical component of natural climate solutions, which rely on quantitative spatial predictions of soil organic carbon (SOC) fractions (particulate organic carbon, POC, and mineral-associated organic carbon, MAOC) across scales. However, our understanding on the drivers of SOC fractions across diverse pedoclimatic zones is not well understood. Here, we show that the drivers of SOC fractions are divergent across pedoclimatic zones at a global scale. We used machine learning with a synthesized global dataset of SOC fractions (11,522 soil samples) to show that, globally, the climate, soil properties (e.g., nitrogen and pH) and elevation are dominant drivers. Nevertheless, we found that such general assessments overlook pedoclimatic zone-specific drivers that influence the distribution of SOC fractions. This oversight can lead to misinterpretations that hinder our understanding of soil C processes and dynamics. Climate exerts its influence through interactions with edaphic factors, topography, and vegetation, however, in certain pedoclimatic zones, its role may be negligible. These results highlight the need for regional assessments of soil C dynamics and more local parameterization of biogeochemical models. Our analysis propounds the development of science-informed and adaptive soil C management under a changing climate.

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# Cover crop species and mixtures drive contrasting vertical distribution of root- and residue-derived C and N in conservation-tilled sandy Ultisols

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**ABSTRACT**

Sandy Coastal Plain Ultisols of the southeastern USA are characterized by critically low soil organic carbon (SOC) and rapid turnover of organic inputs. Using stable isotope probing techniques in strip-till cotton-corn systems, we quantified the allocation and distribution of organic C and N derived from cereal rye (Secale cereale L.), hairy vetch (*Vicia Villosa Roth*), and their mixtures across the soil profile. Pulse labeling revealed contrasting root-C allocation: at the mature stage, rye transferred more newly assimilated $^{13}C$ to 15-30 cm (0.85% of $^{13}C$-$CO_2$) than to 0-15 cm (0.14%), whereas vetch contributed more to 0-15 cm soils (1.17%) than to 15-30 cm (0.41%). Surprisingly, the rye-vetch mixture transferred 1.13% of the $^{13}C$ to 0-15 cm depth but none below 15 cm, demonstrating non-complementary effects on subsoil C allocation. The following field residue ($^{13}C$/$^{15}N$-enriched) decomposition study demonstrated that vetch induced negative priming of native SOC, whereas rye and the rye-vetch mixture did not. At the end of the study, regardless of the cover crops, the topsoil (0-5 cm) retained more residue-derived C, with less found at the depths below (5-20 cm). In contrast, comparable cover crop-derived N was also observed at depths of 5-10 cm and 10-20 cm, reflecting higher mobility of mineralized N. These observations indicated that the cover crop species and mixtures introduced distinctive organic C and N to the soils, either as living plants or as dead residues. Long-term reliance on surface residue retention in conservation tillage systems may lead to C stratification, but less so for N, resulting in C-N decoupling in sandy soils at different depths. Strategic species selection and mixtures are therefore critical for restoring SOC in these vulnerable agroecosystems.

**Keywords:** Cover crop, SOC, stable isotope probing, C stratification, C-N decoupling

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# Crushed basalt application shows soil improvement and potential carbon capture in wheat field

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## ABSTRACT

Enhanced rock weathering (ERW) using silicate minerals such as basalt has emerged as a promising strategy for removing atmospheric carbon dioxide ($CO_2$) while improving soil health and crop productivity. However, the efficiency of $CO_2$ capture through basalt weathering in agricultural soils can depend on several factors, including nitrogen fertiliser inputs that influence soil acidity and nutrient dynamics. This ongoing field study investigates the $CO_2$ capture potential of crushed basalt applied at varying rates under different nitrogen fertiliser applications in an acidic soil ($pH_{CaCl2}$ = 4.94) in South Australia, using wheat (*Triticum aestivum*) as the test crop. The trial consists of 24 plots with three basalt application rates (B1 = 0 t $ha^{-1}$, B2 = 20 t $ha^{-1}$, and B3 = 40 t $ha^{-1}$) and two urea rates (50 and 100 kg $ha^{-1}$), each replicated four times. Basalt sourced from the Moree Quarry in Victoria (p80 = 1,690 µm; i.e., 80% particles less than this size) was surface-applied before seeding. Wheat cultivar "Calibre" was cultivated following standard local practices, with diammonium phosphate applied at sowing and urea broadcast at the three-leaf stage. Soil porewater was collected using macro-rhizon samplers to measure pH, electrical conductivity (EC), alkalinity, and cation concentrations. Soil samples were taken at 0–5, 5–10, 10–20, and 20–40 cm depths at the beginning and end of the growing season to analyse pH, EC, exchangeable cations, organic and inorganic carbon contents, and available nitrogen. Soil enzymatic activities were assayed to understand the biological responses to basalt and nitrogen applications. Crop yield and nutrient uptake were measured at harvest. Porewater pH values 3 months after sowing for B1, B2, and B3 were 6.15, 6.21, and 6.80, while EC values were 703, 980, and 759 µS/cm. Porewater alkalinity was 30.25, 37.16, and 47.1 mg/L $CaCO_3$ for B1, B2, and B3, respectively. The porewater pH and alkalinity increased in basalt-amended plots after 3 months of sowing but the differences were not significant ($p > 0.05$). The mean soil pH value for B1, B2, and B3 at harvest was 4.94, 5.23, and 5.32, respectively, showing a significant variation compared to the control ($p < 0.05$). Soil EC values showed no significant change. Overall, basalt addition enhanced soil pH, indicating early signs of basalt weathering and potential $CO_2$ capture. This paper will present the results of this field ERW study in detail. The findings will provide insight into the interactions between nitrogen fertilisation, soil acidity, and basalt dissolution, contributing to a better understanding of ERW as a carbon sequestration strategy in agricultural systems.

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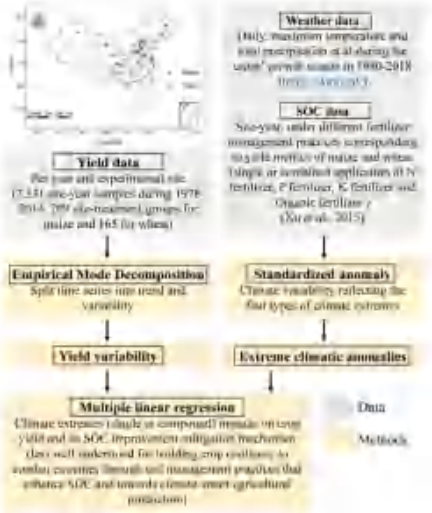
# Soil organic carbon buffers crop yields against climate extremes

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**ABSTRACT**

More extreme climate conditions are threatening global food production. Soil organic carbon (SOC), as a key modulator of soil functionality, may play a critical role in enhancing crop yield against climate extremes. Here, we use a national dataset of 7,331 site-year measurements of maize and wheat yield and SOC content under different fertilizer management practices across China during 1978–2014 to investigate the role of SOC in regulating crop yield responses to climate extremes including heatwaves, cold, droughts and heavy rainfall. The results indicate that SOC along with fertilizer management practices and climatic anomalies explain more than 90% of the variances in detrended yields (i.e., yield deviations from the long-term trend) of both crops. SOC emerged as the most important predictor, alone contributing ~30% to the explained variance for the two crops. Climate extremes quantified by extreme climatic anomalies (i.e., standardized temperature or precipitation anomalies during the crops 'growing season separately with absolute values larger than 1.5, 2.0 and 2.5) led to significant crop yield losses, ranged from $0.79^{0.91}_{0.67}$ t ha$^{-1}$ (mean with 95% confidence interval) to $1.07^{1.19}_{0.94}$ t ha$^{-1}$ and from $0.46^{0.52}_{0.40}$ t ha$^{-1}$ to $0.88^{1.14}_{0.62}$ t ha$^{-1}$ per one standardized anomaly increase in extreme climatic anomalies, with threshold as 1.5, across the four types of extremes, for maize and wheat, respectively. Improving SOC levels with critical values were expected to promote yield gains by 0.6 t ha$^{-1}$ under extremes per 1% increase in SOC content for both maize and wheat, the positive SOC impacts thresholds of where yield changed from loss to gain were respectively 15 g kg$^{-1}$ for maize and 7 g kg$^{-1}$ for wheat with a sliding window of SOC content range as 5 g kg$^{-1}$, and the optimum SOC levels corresponding to no more yield gains with higher SOC accrual were around 21 g kg$^{-1}$ and 9 g kg$^{-1}$ for maize and wheat, respectively. The magnitude of the SOC buffer effects is extremes type- and thresholds-dependent for specific crop. Each 1% increase in SOC content resulted in substantial maize yield gains, ranged from $0.54^{1.07}_{0.01}$ t ha$^{-1}$ to $0.85^{1.35}_{0.34}$ t ha$^{-1}$, under extremes 'thresholds "z >1.5", across the four types of extremes. SOC buffers wheat production against heatwaves and droughts, respectively with yield gains of $1.31^{1.80}_{0.82}$ t ha$^{-1}$ and $1.29^{2.10}_{0.48}$ t ha$^{-1}$ per 1% increase in SOC content, under thresholds scenario "z > 1.5". These positive benefits strengthen under more extreme climatic scenarios (i.e., "z > 2.0" and "z > 2.5"), and can be amplified by adopting improved fertilizer management practices, particularly with the combined application of organic and inorganic fertilizer. Our findings reveal that sufficient SOC sequestration enhance the resilience of crops to climate extremes, highlighting the multiple benefits of improving SOC levels towards critical values for maintaining crop production in a more extreme climate.




A simple structure (Question-Data-Methods) diagram for the research.

# Mapping soil organic carbon across China using ensemble modelling at 30 m spatial resolution

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**ABSTRACT**

Soil organic carbon (SOC) plays a crucial role in food security and climate change mitigation, yet high-resolution spatial mapping of SOC remains challenging over large and heterogeneous areas. This study aims to generate the first national-scale SOC maps of China at 30-m spatial resolution using an ensemble modelling approach. Multi-source soil profile data were integrated with high-resolution environmental covariates representing topography, climate, vegetation, and human activities. Ensemble modelling was applied to predict SOC content and quantify associated uncertainty across multiple soil depths. The resulting maps provide a spatially explicit baseline for assessing soil carbon stocks, supporting climate-smart land management, and informing policies related to carbon neutrality and sustainable agriculture in China.

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# Deep soil carbon accrual by perennial energy crops offers large potential for atmospheric $CO_2$ removal

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## ABSTRACT

As global efforts to mitigate climate change intensify, scalable and sustainable carbon dioxide removal (CDR) strategies are essential to meet the 2 °C target set by the Paris Agreement[1]. Traditional soil-based CDR approaches have focused on topsoil (0–0.3 m), where a significant portion of soil organic carbon (SOC) is stored[2]. However, over 60% of global SOC resides in deeper soils (>0.3 m), which remain largely underutilized in most CDR frameworks. Perennial energy crops, such as Miscanthus, switchgrass, and woody species like poplar, willow, and Eucalyptus, present a promising, low-input solution for tapping into this largely overlooked deep soil carbon pool. These crops, with their deep and long-lived root systems, can enhance SOC accrual through root biomass and rhizodeposition, which may play a crucial role in removing atmospheric $CO_2$.

Here, we conduct the first global synthesis of perennial energy crops-driven SOC accrual across soil depths, integrating 1,161 paired field observations from 28 countries (1980–2025). We show that perennial energy crops increase global SOC by 15.4%, with deep soils (>0.3 m) contributing 59% of the total gains. Specifically, deep soils exhibit a 21.2% increase in SOC, significantly outperforming topsoil, which sees a 14.6% increase. Scaling these results to all potentially adaptable non-forest lands reveal that perennial energy crops could remove up to 408.8 Pg $CO_2$ from the atmosphere—approximately 1.7 times the global fossil $CO_2$ emissions from 2018–2024. Even when excluding croplands to safeguard food security, this approach could still offset >60% of emissions.

Our findings demonstrate that deep soil carbon accrual under perennial energy crops offers a substantial, cost-effective CDR strategy with co-benefits for land restoration and energy production. This approach is particularly impactful in regions with abundant marginal lands, including Oceania, and Africa. Integrating deep soil dynamics into national carbon budgets and international CDR frameworks could substantially enhance the realism and effectiveness of global climate change mitigation strategies, aligning with pathways to limit warming to 2°C.
Keyword: Deep soil; Perennial energy crop; SOC gain; $CO_2$ removal.

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# Soil Organic Carbon Assessment Across Land-Use and Management Scenarios in a Metropolitan Urban–Rural Territory

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## ABSTRACT

Metropolitan authorities overseeing mixed urban, peri-urban, and agricultural areas play a central role in shaping territorial trajectories through planning and incentive-based policies. To implement effective climate strategies, they need a clear understanding of how land-use patterns and management practices across agricultural, natural, and urban spaces may evolve and affect soil organic carbon (SOC) and tree biomass carbon. In line with climate commitments such as the European Green Deal and local climate–energy action plans, they must design strategies that combine emission reductions with enhanced SOC sequestration. Yet land-use change and management practices can either increase SOC or generate losses and $CO_2$ emissions, depending on the chosen trajectory. Existing tools quantify SOC dynamics under agricultural practices or estimate carbon stock changes from land-use conversion, but few approaches jointly consider SOC fluxes, land-use change, and management evolution across mixed urban–rural territories. Interactions between urban expansion and the loss of agricultural or natural soils—and their consequences for SOC—are rarely integrated into a single spatially explicit framework. Such integrated scenarios are essential for assessing the contribution of soils to carbon-neutrality strategies.

This study evaluates SOC and biomass carbon fluxes under four land-use and management scenarios co-developed with stakeholders from the Rennes Metropolitan Area (north-western France). The 705 km² territory includes 510 km² of agricultural and natural land and 195 km² of urban areas. The first scenario extends current trends with ongoing urban expansion and unchanged farming practices. The second introduces moderate improvements in agricultural management and reduced soil conversion. The third represents a transformative shift with major increases in permanent grasslands, boosting SOC storage. The fourth, maximalist scenario converts all agricultural land to forest to estimate the upper bound of carbon sequestration. These scenarios were assessed relative to the current situation to simulate changes in soil and tree-biomass carbon stocks by 2050. Models of varying complexity were used to address uncertainties associated with long-term projections.

Results indicate that all scenarios increase soil organic carbon and biomass stocks. However, even when accounting for model uncertainty, the first two scenarios remain insufficient to offset projected greenhouse gas emissions by 2050. The most ambitious trajectories also show that urban green spaces alone cannot deliver carbon neutrality. Rural soils remain the main SOC sink but also constitute a significant emission source, particularly from grazing systems, highlighting the need for ambitious soil management strategies and cross-territorial compensation mechanisms.

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# Advancing soil organic carbon assessment by integrating fractionated pools, biology, and land-use history across managed landscapes

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## ABSTRACT

Preserving and enhancing soil organic carbon (SOC) requires assessment frameworks that move beyond bulk carbon stocks to capture stabilization mechanisms, biological accessibility, and land-use legacies. However, scalable approaches that integrate these dimensions across heterogeneous landscapes remain limited, constraining soil carbon forecasting and sustainable land management.

We conducted a large-scale soil survey across forest–agriculture mosaics in Atlantic Canada to advance SOC assessment at regional scales. Soils were sampled across a gradient of land-use intensity, spanning wetlands, mature and young forests, perennial pastures, forage-based rotations, and annual cropping systems. At each site, SOC stocks were quantified alongside physically fractionated organic matter pools (labile particulate, intermediate, and mineral-associated fractions), oxidizable carbon (POX-C), microbial DNA analyses, enzyme activities, soil fauna, and key physical and chemical properties. Land-use history over the previous decade was derived from national land-cover inventories and incorporated into spatial analyses.

Total SOC stocks declined systematically with increasing land-use intensity, but losses were dominated by reductions in biologically accessible and intermediate SOC pools (Fig. 1), while mineral-associated carbon showed greater persistence. Biological indicators closely tracked intermediate SOC fractions, highlighting their sensitivity to management and disturbance. Machine-learning models integrating land-use history, terrain attributes, and soil properties substantially improved SOC prediction compared to static land-use classifications alone, revealing strong legacy effects of past management on current SOC status.

Our results demonstrate that integrating SOC fractionation, biological indicators, and land-use history enhances the detection of early SOC degradation and improves regional SOC assessment. This approach provides a scalable pathway to advance SOC science, support sustainable land management, and inform climate-relevant soil carbon monitoring and policy decisions.

**Acknowledgments**

Atlantic Canada data is from project 3040 of Agriculture and Agri-Food Canada (J-002208, J-003623), and PEI Living Labs project (J-002269).

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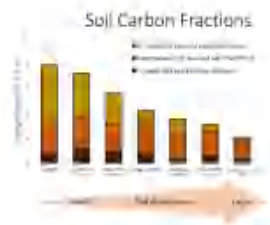



Figure 1. Progressive loss of labile and intermediate soil organic carbon fractions with increasing land-use intensity.

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# Global estimation of soil microbial-derived carbon stocks and its implications for the carbon cycle

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**ABSTRACT**

Microbial-derived carbon (MDC) is a major contributor to persistent soil organic carbon (SOC), yet its estimation methodology, global stocks, spatial heterogeneity, and warming responses remain poorly constrained. Here, we combined 429 soils spanning China (Hailun to Haikou) with global datasets of amino sugars and microbial trait information, and integrated amino sugar biomarkers, $^{13}C$ NMR, high-throughput sequencing, and aerobic/anaerobic temperature-gradient incubations with machine learning and geospatial modelling to address these gaps. To reduce methodological uncertainty, we recalibrated the amino sugar-based conversion factors using expanded pure-strain evidence and community-structure constraints. We proposed the following factors: 31.3 for muramic acid to bacterial-derived C, 10.8 for glucosamine to fungal-derived C, and 1.63 for the bacterial glucosamine-to-muramic acid molar ratio. These updates lowered parameter-related relative errors by 71% while retaining a simple, transferable formula. Applying this framework, we estimated global MDC stocks of 758 Pg in the 0-1 m soil layer (~40% of total SOC), with 65% stored in boreal regions. Using an ensemble machine learning, we mapped MDC stock dynamics across 93.4% of global land from 1981-2018. We detected a mean decline of 6.7 Pg MDC per 1°C warming in predictable areas, with the strongest losses in the tropics. Projections under Shared Socioeconomic Pathways suggest an additional 6-37 Pg reduction by 2100, depending on the selected pathway. Finally, we showed its implications for the carbon cycle: (i) MDC preferentially associates with minerals, contributing on average 54.0% of mineral-associated organic carbon and exhibiting longer turnover than plant-derived C; (ii) the anaerobic incubations indicated that MDC regulated the SOC decomposability and affected the temperature sensitivity of wetland $CH_4$ and $CO_2$ emissions. Together, these results provided a harmonized MDC quantification method and climate-responsive, confidence-aware estimates that can improve carbon-cycle prediction and inform soil management under warming.

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# Soil vertical gradients shape soil respiration but not its temperature sensitivity

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## ABSTRACT

Soil respiration is the largest terrestrial source of $CO_2$ to the atmosphere and a major determinant of carbon-climate feedbacks. Yet which and how vertical gradients in soil physicochemical and biological conditions regulate respiration magnitude and its sensitivity to warming remains unclear. We conducted a five-year in situ incubation with intact 1-meter-deep soil cores along an elevational climate gradient, applying a core-inversion treatment which places soil layers of the same depth-origin into different depths while maintaining overall soil structure integrity. Soil respiration was consistently lower in inverted than in non-inverted cores during the five-year incubation with an average reduction of 24%, demonstrating the importance of depth-associated microenvironmental gradients in shaping soil respiration. However, the climate responsiveness of respiration was independent of the inversion treatment, demonstrating the dominant role of intrinsic carbon substrate properties, which was proved by significant decline in the temperature sensitivity of soil respiration with the proceeding of the incubation. Vertical distribution of substrate chemistry and lability emerged as the key gradients regulating respiration. The findings provide direct, in-situ evidence of environmental constraining of soil respiration, highlighting the importance of explicitly accounting for vertical soil heterogeneity to accurately project carbon-climate feedbacks under climate change.

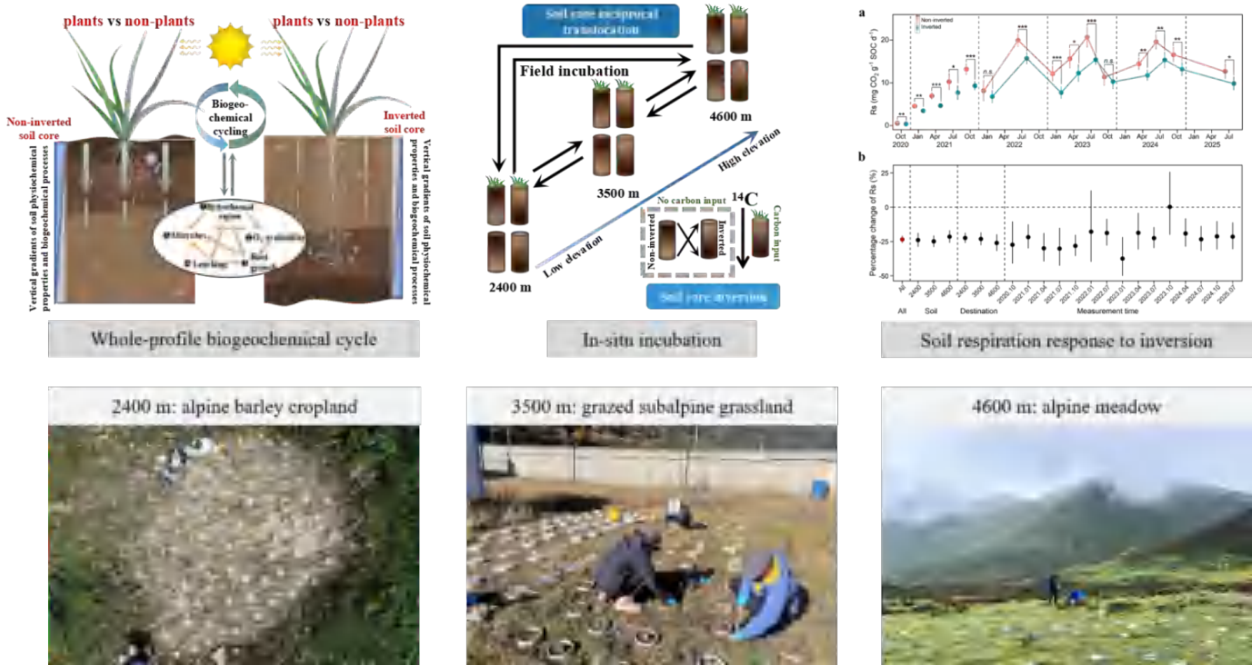



Fig.1 Experimental design and in-situ incubation sites

# Is the tobacco carbon footprint influenced by soil attributes?

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**ABSTRACT**

Quantifying greenhouse gas (GHG) emissions to reduce the impacts of climate change has become a global priority. The carbon footprint, quantified through Life Cycle Assessment (LCA), represents the $CO_2$-equivalent emissions associated with the production of a good or service. In agricultural systems, $CO_2$-equivalent emissions are primarily driven by the use of synthetic fertilisers, particularly nitrogen-based inputs**,** due to both upstream production and field emissions. Nitrogen recommendations are defined based on management practices, soil type, and soil characteristics, particularly chemical properties such as soil organic matter (SOM) content. Fertile soils generally require lower fertiliser inputs and, consequently, present a lower carbon footprint. Tobacco cultivation requires nitrogen inputs to promote leaf development. In this context, the aim of this study was to assess whether management practices, soil texture, soil organic matter content, and regions influence the carbon footprint of tobacco cultivation. The study was conducted in southern Brazil that accounts for approximately 95% of Brazilian tobacco production. A total of 77,132 smallholder farmers data, who delivered their production to British American Tobacco (BAT), between 2020 and 2025, were included in the study. All agricultural inputs were inventoried for the production of 1 kg of cured tobacco. $CO_2$ and $N_2O$ emissions to air were calculated using IPCC (2019) equations, while $NO_x$ emissions were estimated following Nemecek et al. (2016). The carbon footprint was quantified using SimaPro 9.6.0.1. To analyse the factors associated with the carbon footprint, a multiple correlation analysis was performed using R software. Soil type, SOM content, and producing region were significantly correlated with the carbon footprint. Tobacco-producing regions with higher SOM levels required lower nitrogen inputs from synthetic fertilisers, thereby reducing field emissions, particularly $CO_2$ and $N_2O$. The influence of soil type was primarily associated with textural differences, as soils with coarser textures generally exhibit lower aggregation capacity and nutrient retention. Under such conditions, the adoption of cover crops and residue management practices becomes essential to enhance SOM accumulation and improve fertiliser use efficiency. Overall, the results indicate that maintaining soil organic matter plays a central role in mitigating the carbon footprint of tobacco cultivation. Sustainable soil and crop management practices should therefore be encouraged to reduce GHG emissions and support climate change mitigation in agricultural systems.

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# Counteracting warming-induced soil organic matter loss via cyanobacteria-enhanced glomalin-mediated aggregation

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## ABSTRACT

Climate warming, particularly during winter, poses a significant threat to soil organic carbon stability. Integrating global observational data with a decade-long field experiment, we identified a critical negative correlation between winter soil temperature and crop biomass carbon. Our mechanistic investigation revealed that this decline is primarily driven by the warming-induced disruption of mineral protection, which accelerates soil organic matter (SOM) degradation and depletes essential micronutrients (Fig. 1). To counteract these adverse mechanisms and advance sustainable land management, we investigated a bio-based intervention in cold-region Mollisols by inoculating nitrogen-fixing cyanobacteria to partially replace synthetic nitrogen fertilizer. Our results demonstrate that cyanobacterial inoculation not only alleviates plant nitrogen limitation but also stimulates root development and activates mycorrhizal fungi. Crucially, this microbial regulation enhances the secretion of glomalin-related soil protein, which promotes soil macro-aggregation and stabilizes microbial necromass, particularly fungal residues. Consequently, this strategy successfully offsets SOM losses, improving nitrogen use efficiency and increasing crop yield by 7.6%. This study bridges the gap between understanding the biogeochemical drivers of carbon loss and implementing effective, microbe-mediated strategies for agricultural resilience.

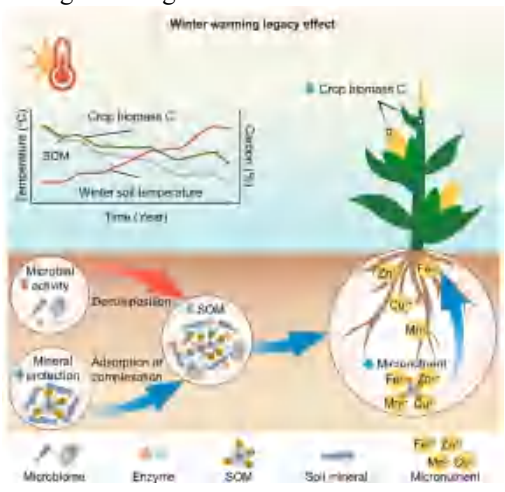



**Fig. 1** Schematic of the legacy effect of winter warming on crop biomass C. The red arrow signifies an intensified process, while the blue arrow denotes a weakened process. The Orange upwards arrow within a variable represents an increase, and the green downwards arrow indicates a decrease. Crop biomass C encompasses both straw C and grain C contents.

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# Land use change and management strategies promoting soil organic carbon sequestration in LAC countries

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**ABSTRACT**

Soil degradation is a major global concern, with land-use conversion central to current debates. A recognized outcome is reduced soil productivity, often linked to agricultural intensification following shifts from native grassland or forest to cropland or pastures. Soil organic carbon (SOC) is a key indicator of soil health and an important potential sink for greenhouse gases (GHG). Thus, management alternatives that increase SOC promote sustainability while mitigating GHG emissions. In Latin America and the Caribbean (LAC) local data on SOC stocks due to land use and management changes is scarce. This cooperation between Argentina, Chile, Colombia, Costa Rica and Uruguay aims to design land use and management strategies for key LAC production systems with high carbon sequestration potential, reducing knowledge gaps, strengthening capacities and generating References SOC data to improve GHG inventories. Soil sampling campaigns following harmonized protocols were conducted in 2023-2024 at contrasting long-term land use and management paired sites, with samples collected at 0–10, 10–30, and 30–60 cm. Soils were analyzed for organic carbon (C), nitrogen (N), stable isotopes ($^{13}C/^{12}C$ and $^{15}N/^{14}N$), and for developing a NIRS calibration library for SOC and organic N quantification. A database integrating 25 long-term experiments and 240 farms (including 29 land use changes) is under development. This extensive database allows updating References values and emission factors in IPCC SOC tables (from Tier 1 to Tier 2, or even Tier 3) for key cropland, grassland and forestland systems. Using this updated tool, one major opportunity for soil carbon sequestration will be evaluated for each participating country, performing an economic assessment and GHG balance analyses, based on international methodologies (IPCC guidelines, Monte-Carlo simulation and Life Cycle Assessment, respectively). The project has strengthened local capacities to quantify, monitor and report changes in SOC stocks, as well as associated economic and GHG metrics relevant for LAC countries beyond this cooperation.

This innovative and ambitious initiative provides a foundation for policymakers to promote sustainable strategies that enhance SOC stocks through robust local evidence, generating benefits for farmers by improving soil health and productivity while contributing to global climate-change mitigation.

**Acknowledgments**

The project is funded by FONTAGRO and the New Zealand Government as part of its contribution to the Global Research Alliance on Agricultural Greenhouse Gases (GRA). Main leader executing agency is INIA (Uruguay), with co-executing partnership of INTA (Argentina), INIA (Chile), Agrosavia (Colombia), and INTA (Costa Rica). Associated partners are MGAP (Uruguay), MAGYP (Argentina), CIAT (Nicaragua) and the Ohio State University (USA).

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# Quantifying non-linear relationships and causal effects of soil organic carbon on crop productivity stability

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**ABSTRACT**

Food security is one of the defining challenges of our century, yet sustaining agricultural production is becoming increasingly precarious under accelerating climate change. Building soil organic carbon (SOC) stocks is known to improve yields; however, whether SOC can buffer agriculture against fluctuations in crop productivity remains uncertain. Evidence to date has been restricted to small-scale in situ trials, leaving its stabilizing role at larger spatial and temporal scales unexplored.

Here, we firstly quantified the relationships between SOC and stability of crop productivity across China's croplands from 2001 to 2020 using a combination of Generalized Additive Mixed Models (GAMMs) and XGBoost models with SHAP explanation framework. Vegetation indices (NIRv), Solar-Induced Chlorophyll Fluorescence (SIF), and MODIS gross primary productivity (MODIS GPP) were used as proxies for crop productivity, while their detrended interannual coefficient of variation (CV) served as a measure of stability. Across model types, results across two decades consistently showed that maintaining higher SOC content in croplands, results in more stable crop productivity. We observed critical thresholds of SOC content (maize: 10.2 – 13.4 g/kg; wheat: 8.6 – 9.9 g/kg), above which high SOC content leads to more stable crop productivity. After determining the positive relationships, we investigated marginal causal effect of SOC using causal forest double machine learning models. Results indicated that increasing one unit (g/kg) of SOC can reduce the CV of crop productivity by 1.09% to 2.08% on average nationally. Specially, in regions with lower SOC levels, the marginal benefits of increasing SOC are more pronounced, particularly in areas characterized by lower soil structure and greater climate variability. In these environment-limited croplands, increasing SOC can play a more significant role in maintaining sustainable agriculture.

Our results emphasize SOC's role in building resilient food systems. This improved understanding can refine the representation of soil carbon in earth system models and highlight the importance of soil carbon sequestration in croplands under climate change.

**Acknowledgments**

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# Integrating Remote Sensing and Process-Based Modeling to Assess Grassland Soil Organic Carbon Change

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**ABSTRACT**

The preservation and enhancement of soil organic carbon (SOC) in grasslands are essential for maintaining soil health, supporting ecosystem services, and contributing to climate change mitigation. This study applies the RothC model to investigate SOC dynamics in MRV4SOC grassland demosite in Wallonia, Belgium, with the objective of producing an assessment of SOC stock changes at landscale scale, consisting of approximately 34,000 fields. Model simulations based on in-situ measurements on this ICOS station are compared with the simulations using remote sensing (RS) inputs. This comparison enables assessing the sensitivity of SOC stock modelling to input replacement. RS data, agricultural census datasets, and existing soil maps are used to derive key boundary conditions for both the demosite and landscape scale, with a particular emphasis on estimating carbon inputs from grassland biomass production and livestock excreta. RS inputs extracted from raster maps were calculated as mean pixel values per field to run the model at the field level across the landscape. At the demosite scale, the sensitivity of the RothC model to the replacement of measured data with RS boundary conditions showed that the largest variation in delta SOC stocks compared to model using in-situ inputs, were driven by initial SOC stock values obtained from available maps, followed by climate data from ERA5 reanalysis products. The difference in SOC stock changes between the two model (all RS vs all in-situ inputs) was 1.3 t C $ha^{-1}$ over the four-year simulation period from 2021 to 2024, which was considered the sensitivity range associated with RS data. At the landscape scale, the mean predicted SOC change across grassland fields was 2.1 t C $ha^{-1}$. When accounting for the sensitivity range, results indicated that more than 80 % of grasslands at landscape scale are predicted to have an increase in SOC stock over the past four years. This increase was particularly observed in fields with lower initial SOC stock. This pattern is consistent with trends observed in some long-term experimental sites in Wallonia, where changes in carbon inputs from biomass and therefore changes in SOC stocks reflects the effects of agricultural management activities. By integrating site-level observations from the demosite with spatial modeling, the study highlights the spatial variability of SOC responses to carbon inputs and environmental conditions. Overall, this work represents a step toward generating spatially continuous maps of SOC stock change in grasslands, providing a scalable framework to support carbon sequestration strategies.

**Acknowledgments**

MRV4SOC project is funded by the European Union under the Grant agreement No. 101112754. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the granting authority can be held responsible for them.

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# National Scale Mapping of Soil Organic Carbon Vulnerability Indicators in New Zealand

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**ABSTRACT**

Soil organic carbon (SOC) is a key indicator of soil health and is vital for many soil functions and associated ecosystem services. However, abundant literature shows SOC to be highly vulnerable to climate change or changes in land use. There is urgent need to understand the vulnerability of these soils to changes in climate or in land use, and the impact these changes will have on SOC. This understanding is not only important for maintaining or increasing soil health but is essential to understand how any potential change will impact atmospheric carbon dioxide concentrations.

The partition of total SOC into pools of different mean residence time has been used to understand the vulnerability of SOC to loss or the potential to further increase SOC, and can allow better understanding of how management, land use, or climate effects may impact stocks of SOC. The way these different forms of SOC reside in the soil has also been shown to be important, and recent work has demonstrated that the relationship between SOC fractions and mineral surface area (MSA). In this study, we investigate how the combination of spatial predictions of SOC fractions and MSA could be a useful tool to assess the vulnerability of SOC.

As those methods are cost and time intensive, the use of spectroscopy was investigated to predict the data in a more time and cost-effective way. SOC fractions and MSA were modelled from mid-infrared spectroscopy (MIR) based on a set of 302 soil samples, representative of New Zealand's agricultural land. Cross-validation results showed that most models fitted for the properties of interest in this study were very satisfactory, with CCC and R^2≥0.9, and limited bias.

Predictions for these properties were generated for the NZ Soil Spectra Library (NZ-SSL), which is a large collection of soil spectra recorded from soils all around NZ. The NZ-SSL has a total of 55,081 MIR spectra, corresponding to 11,570 individual soil samples. Those spectral estimates were used as input for the digital soil mapping (DSM) of those properties at the national scale, onto a grid of 1 km resolution, and drawing on empirical relationships between those properties and a range of environmental covariates. The results show that the performance of the DSM models fitted in this project is limited, with CCC values around 0.5, and $R^2$ values around 0.3. This level of performance, however, matches that obtained by authors mapping SOC fractions in other countries. The resulting spatial layers obtained via DSM for total SOC, SOC fractions, and MSA were then combined into a series of SOC sequestration indicators. In the last part of this study, we investigate the pertinence and geography of those indicators.

# Unraveling the Interconnections of Soil Organic Carbon Dynamics in Sustainable Land Management

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**ABSTRACT**

The significance of soil organic carbon (SOC) in promoting sustainable agricultural practices and enhancing ecosystem resilience is well-established, yet the complexity of its dynamics necessitates further investigation. The proposed research focuses on two critical aspects. The first aspect investigates the causal mechanisms linking farmland infrastructure and crop diversity to stable agricultural production and carbon sequestration. Specifically, the role of infrastructural elements—such as land layout and field access pathways—in enhancing farmland resilience to climatic stressors, including drought, extreme heat, and flooding, will be analyzed. This investigation combines empirical data and case studies to elucidate the supporting effects of these infrastructures on agricultural systems. The second aspect addresses the impact of diversified cropping patterns—specifically intercropping and crop rotation—on yield responses, water use efficiency, and the modulation of soil carbon stocks under conditions of climate-induced stress. The findings will provide insights into the regulatory mechanisms that underpin these relationships, illustrating how diversified agricultural practices can facilitate SOC enhancement while productivity.

Engagement at this conference will facilitate the exchange of knowledge among researchers, practitioners, and policymakers, fostering interdisciplinary collaboration in the realm of SOC science. The outcomes of this research are anticipated to inform the development of strategies that promote sustainable land management, ultimately contributing to the enhancement of soil health, agricultural productivity, and climate resilience. This ABSTRACT is submitted with the objective of stimulating academic discussion and advancing the collective understanding soil organic carbon dynamics and their implications for sustainable land management. Thank you for considering this contribution.

**Acknowledgments**

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# Response of soil organic carbon to the changes in plant productivity under warming

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**ABSTRACT**

Soils can be either a source or sink of atmospheric $CO_2$ depending on how soil organic carbon (SOC) responds to climate warming and changes in plant productivity. While warming typically accelerates SOC decomposition, the effect of plant productivity changes remains unclear. Here we use a space-for-change substitution approach to analyse a global dataset of SOC measurements down to 1 metre. We find that warming-induced SOC reduction in the 0–0.3 m topsoil is gradually offset by increasing plant productivity, but exacerbated in the 0.3–1 m subsoil until plant productivity increase crosses a threshold of 30%. Consequently, entirely offsetting warming-induced SOC reduction in the top metre of soil requires an unrealistically high increase in plant productivity, albeit with substantial variance across ecosystems. Soil carbon-to-nitrogen ratio is the dominant predictor of the variance in SOC response, as this ratio determines whether nitrogen released during carbon loss meets the requirement for additional plant growth or whether additional nitrogen must be mined from soil organic matter. Such mining accelerates SOC losses, particularly in the subsoil, where the soil carbon-to-nitrogen ratio is lower than in topsoils. We conclude that globally, increased plant productivity may exacerbate SOC losses under climate warming, particularly in the subsoil.

**Acknowledgments**

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# Vegetation restoration of degraded meadows by non-dominant species decreased cumulative $CO_2$ emissions and temperature sensitivity of soil respiration rates

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**ABSTRACT**

Alpine meadow degradations are common across the world. Degradation and restoration of meadow soils that have large carbon (C) and nitrogen (N) pools will cause substantial changes in soil C and N compositions as well as soil respiration that emits carbon dioxide ($CO_2$) to atmosphere. Vegetation restoration using multiple species with different origins may impose divergent effects on soil C and N status and hence respiration rates (*Rs*) due to their differences in functional characteristics. To understand the effects of meadow degradation and vegetation restorations by historically non-dominant species on $CO_2$ emissions, we measured *Rs* in meadow soils experiencing degradation or restoration using originally dominant or non-dominant species. Soil respiration rates and soil C and N variables were measured over twelve months *in situ* from randomly selected plots with five treatments: seriously degraded meadows (bare land), restored meadows using historically non-dominant (*Carex chinensis* or *Fimbristylis dichotoma*) or dominant species (*Miscanthus floridulus*), and non-degraded meadow (with original *M. floridulus*). Meadow degradation and vegetation restoration significantly impacted soil C and N variables and cumulative $CO_2$ emissions. Microbial biomass C and N, as well as dissolved organic C and nitrate N were most distinct among meadow plots of different treatments. Degradation to bare land decreased multiple C and N variables compared with non-degraded meadows. Restorations using historically non-dominant species consistently decreased temperature sensitivity of *Rs*. Contributions of C and N variables depended on the species used for restoration. Effects of meadow ecosystem degradation and restoration are important for C and N cycling. Due to the distinct effects imposed by restoration species on soil respiration, both functional group and species identity should be considered in future management and restorations of degraded meadows in terms of their profound impact on global C cycling and mitigation of climate change.

***Keywords:*** Mountain meadow degradation, respiration rates, carbon mineralization, vegetation restoration, dominant species

# Refining the RothC Model's Decomposition Rate Modifier for Moisture to Improve Soil Organic Carbon Estimation in Paddy Fields

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**ABSTRACT**

The Rothamsted Carbon (RothC) model is a widely used process-based model for estimating soil organic carbon (SOC) dynamics, offering simple input requirements and strong performance in croplands. However, it does not explicitly represent reductions in decomposition rates under saturated soil conditions, limiting its applicability to paddy systems characterized by irrigation-induced flooding-drainage cycles. To address this, a paddy coefficient developed in Japan (Shirato & Yokozawa, 2005) has been commonly applied in SOC estimation in the RothC model. Nevertheless, this approach relies on fixed seasonal values (0.2 in summer and 0.6 in winter), which introduces uncertainty by failing to capture the gradual and continuous soil moisture dynamics associated with irrigation management in paddy soils. In this study, we structurally refined the decomposition rate modifier for moisture (b) in the RothC model to improve SOC estimation in paddy soils. First, a soil hydrological model (HYDRUS) was integrated to simulate temporal variations in soil water content based on climate, soil, crop, and irrigation input data. The simulated soil water content was used to calculate the b modifier. Second, the b modifier was reformulated so that it decreases linearly as soil moisture approaches saturation, allowing a continuous representation of decomposition rate reduction under dynamic soil water conditions. The refined RothC model was validated using long-term data (9-54 years) from four experimental sites in South Korea and was further extended to assess SOC stocks in paddy soils at the national scale. The refined RothC model showed a modest overall improvement in predictive performance ($R^2$ = 0.97, RMSE = 4.18 ton C $ha^{-1}$), particularly under high organic inputs such as manure application. This improvement reflects a more realistic representation of SOC decomposition responses to soil moisture dynamics and rewetting effects occurring under irrigation-driven flooding-drainage cycles. By directly linking HYDRUS-based soil moisture simulations to the RothC model, this study demonstrates that structural refinement accounting for paddy soil moisture dynamics can enhance the reliability of SOC estimation. This process-based framework improves SOC assessment and forecasting under irrigated paddy management, with implications for sustainable land management and national greenhouse gas inventories.

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# Urban soils carbon across the scales and regions: who and what drive the spatio-temporal variability of soil carbon in urban areas

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**ABSTRACT**

Carbon neutrality is considered as the key strategy for climate mitigation. Cities which are responsible for a major part of anthropogenic C emissions invest in development of urban green infrastructures (UGI) to compensate these emissions by C sequestration in biomass. The role of urban soils in UGI C balance remains overlooked resulting in uncertainty in the estimated capacity of UGI to accumulate and store C. In fact, urban soils can be considered a social-ecological phenomena since direct and indirect anthropogenic drivers have the main impact on soil functionality and ecosystem services including C sequestration.

The research integrates several case studies, where direct and indirect anthropogenic effects distinguished spatio-temporal patterns in C stocks in and $CO_2$ emission from urban soils in different bioclimatic regions and at different scales. The first case study focused on the effects of urban mesoclimatic anomalies and soil construction practices in six cities in Central European Russia. Cities are different in climatic conditions (from subarctic to semiarid), size and history. In all cities, urban heat island (UHI) effect accelerated $CO_2$ emissions from urban soils with the most remarkable consequences in Moscow city center, where implementation of peat-sand mixtures coincided with the strongest UHI, $CO_2$ emissions increased up to 30-40% compared to the References cites. The second case study compared environmental and social drivers of spatial variability in soil C stocks in two Dutch cities: Amsterdam and Wageningen. The study in Amsterdam is based on the dataset collected by municipal services, processed based on the distinguished spatial predictors and verified based on the field survey. The study in Wageningen included several scales. First, a random stratified soil survey (n=56) was done for the whole city to capture the effect of parent materials, land cover and land-use history. Afterwards, effect of the social factor was studied by expert interviews with the owners of the green areas (key plots, n=10), where detailed soil survey was done. Finally, the effects of UGI maintenance practices were studied for the case of university campus. Land-cover and land-use history distinguished spatial patterns in soil C at the city level, whereas at the local scale social factors dominated.

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# Depth Variations and Drivers of Soil Organic Carbon in Croplands of the Black Soil Region, Northeast China

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## ABSTRACT

Understanding the distribution of soil organic carbon (SOC) at different depths and its environmental regulation mechanisms is crucial for managing soil health and enhancing carbon sequestration potential. However, comprehensive field data quantifying the nonlinear responses of SOC to environmental drivers in specific regions are scarce. This study analyzed SOC content from 120 cropland soil profiles (0–100 cm) to investigate the horizontal and vertical patterns of SOC, using the western Songnen Plain as a representative case. A threshold model was then applied to quantify the nonlinear relationships between SOC content and key environmental factors. Results showed that SOC content decreased sharply with depth, from 13.38 ± 8.18 g·kg$^{-1}$ (0–20 cm) to 4.37 ± 2.81 g·kg$^{-1}$ (80–100 cm), with the surface layer storing approximately three times more SOC. The primary factors influencing SOC content variation were clay content (Clay), mean annual temperature (MAT), carbon input (CI), bulk density (BD) and pH. Notably, abrupt SOC changes were triggered when these factors crossed specific thresholds, including Clay at 1.38 g·kg$^{-1}$ (in 0–20 cm), MAT at 4.7 ℃ and CI at 3.2 t C ha$^{-1}$ (in 0–40 cm), BD at 1.55 g·cm$^{-3}$ (in 40–100 cm), and pH at 7.5 and 8.9 (in 40–100 cm). This study provides an updated assessment of SOC content in the western Songnen Plain and confirms that SOC content undergoes abrupt changes at specific environmental thresholds. These findings provide theoretical support for optimizing soil management strategies in croplands of the Northeast Black Soil Region.

**Keywords:** Cropland; Deep soil organic carbon; Northeast China; Soil profile; Threshold diagnosis



**Fig. 1** The study area and soil sample points



**Fig.2** Data collection and processing: (a) representative Soil Profile Sapling Points and excavating whole-soil-profiles in the order of the occurrence layer; (b) Sketch map of distribution by standardization



**Fig. 3** Spatial distribution of SOC content in the study area at (a) 0–20cm, (b) 20–40cm, (c) 40–60cm, (d) 60–80, and (e) 80–100 cm, respectively.



**Fig. 4** SHAP values and MAS values represent feature importance of all variables in RF across various soil layers. SHAP values illustrate both the magnitude and direction of feature effects on the model output. Colors represent the feature values (orange indicates high values, blue indicates low values). SHAP values are provided for each horizontal position of each point; If the feature value is positively correlated with the SHAP value, the variable is considered to influence the SOC content.



**Fig. 5** Dependency plots of SHAP main-effect values against the environmental variables (MAT, pH, BD, Clay, and CI) at the following soil depths: 0–20 cm (blue point, a–c), 20–40cm (green point, d–f), 40–60cm (purple point, g–i), 60–80cm (brown point, j–l), 80–100cm (gray point, m–o). Red letters along the black dashed line denote the environmental thresholds where changes in the SOC content gradient occur.

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# Assessing pedotransfer functions for bulk density to improve predictions of soil carbon stocks in Retisols (Moscow region, boreal zone)

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**ABSTRACT**

Soil bulk density (BD) is rarely measured in soil studies due to the high cost and labour intensity involved. However, data on soil density is necessary for assessing nutrient stocks and flows in the soil. Pedotransfer functions (PTFs) can be used to estimate BD indirectly based on more readily available data.

Research objectives: (1) Identify the soil properties that are most strongly correlated with BD,(2) Evaluate the accuracy of literature-based PTFs for predicting BD in the study area, (3) Analyse the natural variation of BD across land use types and compare it with the variation introduced by PTF estimations.

The study was conducted at the Chashnikovo Training and Experimental Soil Ecology Center of Moscow State University. Retisols (WRB, 2022) represent the soil cover. Samples were collected from six key plots, which represent different natural and anthropogenic landscapes. Three soil profiles were excavated per plot. Soil samples were taken in duplicate at 10 cm intervals using 100 $cm^3$ steel cores to determine bulk density (BD) and analysed for moisture content (W), particle size distribution according to the USDA classification and organic carbon (OC) content. The total number of samples was 90.

The strongest correlations with BD were found for sampling depth and soil organic carbon content. Thirty out of the 48 PTFs tested achieved an $R^2$ greater than 0.75. Based on the performance indices of mean error (ME) and root mean square error (RMSE), five PTFs were identified as the most accurate for the studied Retisols. Functions F3 and F8 (Abdelbaki, 2018), which use OC as a predictor, and functions F23 and F34, which use OM, showed RMSE values between 0.09 and 0.12 $g*cm^{-3}$. The highest accuracy ($R^2$ = 0.81, ME = 0.73) was achieved by function F24, which incorporated five predictors: OC, W, clay, depth and silt content.

Analysis of BD variation revealed that natural BD variation across different land uses often exceeded the PTF prediction range. Consequently, PTFs may significantly over- or underestimate BD and frequently fail to capture the full scope of natural variability.

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# Depth-resolved soil organic carbon estimation: a scalable approach

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**ABSTRACT**

Soils are central to the global carbon (C) cycle, supporting climate change mitigation and essential ecosystem services. While research often focuses on topsoil (<30 cm), subsoils store a substantial share of total C due to their larger volume and lower vulnerability to disturbance. Yet, subsoil C dynamics remain poorly understood, limiting their integration into models and policy. Many soil organic carbon (SOC) models focus on only the topsoil as a single uniform layer, but differences in soil properties, microbial activity, and the sources and pathways of C inputs at greater depths mean that multi-layer and whole-profile approaches are needed. Land use and management strongly influence soil organic carbon by shaping plant traits such as root depth, architecture, and the presence of nitrogen-fixing species. These traits vary markedly between native vegetation, agricultural pastures, and crop systems. Cropping practices, such as fertilisation, tillage, stubble retention, and rotations, alter C input quantity, quality, and depth distribution. For example, fertilisation boosts biomass, increasing above- and below-ground inputs, while deep-rooted crops like canola enhance subsoil C.

Despite widespread use of process-based SOC models at the surface, scalable frameworks for predicting SOC throughout entire soil profiles remain limited. This study applies RothPC-1, a layered extension of RothC, to estimate SOC stocks to depth using readily available data. RothPC uses five conceptual C pools with distinct decomposition rates to simulate SOC dynamics. We applied the model at 164 sites in New South Wales, Australia, across five land uses: irrigated cropping, dryland cropping, grazing modified pasture, grazing native vegetation and unmanaged native vegetation. C inputs were derived from remote-sensing evapotranspiration and NDVI and scaled by land use. The model showed strong agreement between predicted and observed profile SOC stocks ($R^2$ = 0.39–0.97; RMSE = 2.0–24.7 t C $ha^{-1}$), comparable to other depth-resolved models. Grazing native vegetation performed best, likely due to limited management impacts and more uniform soil types. Irrigated cropping performed the worst, highlighting a need to adjust the model to account for irrigation events. Scaling factors for C inputs across land uses were higher for dryland cropping, native and modified pasture grazing and compared to unmanaged native vegetation, likely due to a combination of increased animal and fertiliser inputs and differing plant physiology and species composition. Our findings demonstrate RothPC-1's capability to estimate SOC to depth using accessible datasets and underscore the importance of deeper sampling to refine parameters and improve accuracy. The framework's scalability offers opportunities for carbon farming and national SOC accounting beyond the topsoil.

# Aridity-driven soil carbon vulnerability to drought shapes future carbon–climate feedbacks

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**ABSTRACT**

Drought frequency and intensity are increasing globally, with uncertain consequences for soil organic carbon (SOC) dynamics in grasslands and shrublands. Using the International Drought Experiment (IDE) network, we quantified how total SOC and its key fractions—particulate organic carbon (POC) and mineral-associated organic carbon (MAOC)—respond to extreme, 1-in-100-year droughts imposed for 1–5 years across 19 sites spanning broad climatic and edaphic gradients worldwide. Across all sites, drought caused no overall change in SOC, POC, or MAOC concentrations. However, responses varied strongly with aridity. In mesic ecosystems (aridity index, AI > 0.65), SOC and POC concentrations declined significantly by 7.9 ± 3.9% and 15.9 ± 6.2%, respectively, whereas MAOC remained stable. In contrast, no significant changes were detected in drylands (AI < 0.65). The sensitivity thresholds of SOC and POC to drought (AI ≈ 0.61 and 0.58, respectively) coincided with the transition between mesic and dryland systems, highlighting aridity as a primary control. Declines in POC under drought were linked to reduced plant productivity and enhanced microbial turnover, while stable MAOC indicated resilience of mineral-bound carbon. In C-rich mesic soils, drought amplified microbial decomposition and priming, leading to measurable SOC losses. Conversely, high interannual precipitation variability and low substrate availability buffered drylands against further carbon depletion. Our results provide the first globally consistent experimental evidence that aridity governs the direction and magnitude of SOC responses to drought. These findings reveal that future increases in drought frequency will disproportionately deplete labile carbon pools in mesic regions, potentially weakening their role as terrestrial carbon sinks. Incorporating differential sensitivities of POC and MAOC into Earth system models will improve predictions of soil carbon–climate feedbacks under intensifying aridity.

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# Rotational grazing with no-till can efficiently maintain soil carbon stocks in Mediterranean woody pastures but results in lower microbial abundance and fungal diversity than grazing abandonment

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**ABSTRACT**

Rotational grazing (RG) with no-till has been proposed as a sustainable alternative to grazing abandonment (GA) to restore soil health and biodiversity in Mediterranean woody pastures, which are crucial for climate mitigation due to their great ecological and socioeconomic importance and the key role these systems play in carbon sequestration and sustainability (Ishaq et al., 2025). To evaluate their effects on soil carbon storage and on the soil microbiome, these two management systems were compared in a dehesa in Extremadura (Spain). RG increased pH, field capacity, and nitrate and Mg content, whereas GA accumulated more total organic carbon (14.6 vs. 10.7 g $kg^{-1}$). Total microbial biomass was 65% higher under GA, but the fungi/bacteria ratio increased under RG, suggesting improved soil structural stability. In both systems, Actinobacteriota, Proteobacteria and Chloroflexi dominated the prokaryotic community, Ascomycota and Basidiomycota dominated fungi, and TSAR and Archaeplastida supergroups prevailed amongst the protistan community. In GA, however, a higher relative abundance of beneficial prokaryotic and fungal taxa (such as *Bacillus*, *Sphingomonas, Streptomyces, Mortierella*, etc.) was found than in RG. In regards of protists, consumer groups such as Cercozoa and Ciliophora presented a high prevalence in both systems, indicating stability despite compositional shifts. Venn diagrams revealed 3121 prokaryotic ASVs exclusive to RG and 2836 to GA, while for fungi 581 ASVs were exclusive to RG and 795 to GA, confirming a strong compositional turnover. Alpha diversity differed across groups. Fungal richness and Shannon index were significantly higher in GA ($p < 0.05$), while prokaryotic and protist diversity (ASVs and Shannon indices) remained similar between treatments, confirming a selective effect of management on fungi. A redundancy analysis including soil physicochemical parameters explained 57% of prokaryotic and 21% of fungal community variance, with pH, Mg, vegetation cover and soil organic carbon as main drivers. RG was associated with nutrient availability and structural resilience, while GA correlated with vegetation cover. Overall, GA promoted microbial abundance and beneficial microorganisms, whereas RG maintained soil carbon stocks and functionality. Integrating both strategies could maximize soil carbon sequestration in Mediterranean pastures.

**Acknowledgments**

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# Soil carbon mineralization decreased in desert steppe by light grazing but not fencing management

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## ABSTRACT

Fencing off grassland soils emits massive amounts of carbon into the atmosphere. Whether grazing management in desert steppes with fragile ecosystems can mitigate this trend remains highly uncertain. Here, we examined how soil carbon mineralization, as well as its underlying mechanisms, varied with grazing intensity by sheep in a long-term (17-year) experiment in the desert steppe. Carbon mineralization decreased by 15%-55% under different grazing intensities compared to fencing controls. Soil organic carbon (SOC) maintained high levels under light grazing, whereas it decreased with increasing grazing intensity. Reductions in plant carbon and absolute microbial abundance due to grazing, coupled with changes in soil carbon quality and the environment, drove the reduction in carbon mineralization. We suggest that mechanisms of carbon mineralization can be integrated into predictive modelling efforts to better understand the impact of grazing on carbon fluxes in ecologically fragile, but globally important, arid and semi-arid grasslands.

# Grazing disturbance reduces soil organic carbon sequestration and stability in desert steppe

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## ABSTRACT

While grazing effects on soil organic carbon (SOC) stocks are documented, how stocking rates repartition carbon between labile and stable fractions in desert steppes remains unknown. Previous studies have focused predominantly on individual carbon pool stocks rather than on inter-component equilibrium. Here, we evaluated the results of a twenty-year controlled grazing experiment, systematically analyzing how prolonged stocking pressure alters the proportional stability of particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) by disrupting the formation of POC and MAOC from plant and microbial precursors. We found that, despite maintaining stable proportions relative to total SOC, POC and MAOC sub-pools exhibited parallel declines under overgrazing. This demonstrates that SOC destabilization arises from systemic changes to carbon repartitioning rather than from isolated pool depletion. Grazing-induced shifts in plant community composition and soil structural features impaired microbial functionality and enzymatic processes, limiting the transformation of organic substrates into more stable forms of soil carbon. These findings advance desert steppe management by highlighting the importance of prioritizing component ratio stability over conventional stock-based metrics and offers actionable strategies to balance carbon sequestration.

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# Mechanism of increased drought intensity stimulating the extracellular polymeric substance (EPS) accumulation and their contribution to soil organic carbon

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## ABSTRACT

Under global climate change, precipitation regimes are increasingly exhibiting trends of diversification and extremization. In arid regions, precipitation acts as a key driver for the formation and stabilization of soil organic carbon (SOC), making microbial necromass and extracellular polymeric substances (EPS) central to the long-term stability of SOC. Changes in precipitation may alter the carbon allocation strategies of soil microorganisms, thereby influencing the differential environmental responses and turnover capacities of microbial necromass and EPS. However, the mechanisms underlying how long-term precipitation alterations affect the composition of soil carbon-fixing bacterial communities and their impact on the dynamics of EPS and microbial necromass, as well as the factors regulating them remain poorly understood. To address this knowledge gap, we conducted a 9-year precipitation manipulation experiment with five treatments: ambient precipitation as the control, along with 40% and 20% reductions in precipitation, and 20% and 40% increases in precipitation. Although changes in precipitation did not alter soil fungal diversity indices, they modified the composition and function of dominant fungal communities. Increased precipitation promoted overall bacterial diversity but reduced the diversity of *cbbM*-carrying bacteria. Under reduced precipitation conditions, drought-tolerant Proteobacteria dominated the *cbbM*-harboring bacterial community, resulting in an increase in their relative abundance from 8.9% to 15.6%. Under extreme drought conditions, microbial necromass and EPS contents decreased by 76.0% and 30.2%, respectively. Increased drought intensity raised the EPS accumulation coefficient (24.8–41.0%), suggesting that EPS was either more efficiently formed or accumulated as a microbial residue. Overall, long-term drought shifted microbial community structure, redirecting carbon allocation from biomass growth and necromass formation toward EPS production. This shift in microbial residue composition may represent a key mechanism for SOC sequestration under drought conditions. This study provides direct and novel evidence that EPS contributes more actively than microbial necromass to SOC in response to long-term drought.

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# Microplastics from conventional and biodegradable mulch films alter microbial necromass accumulation and organic carbon sequestration

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## ABSTRACT

Plastic films play an important role in achieving food security for a growing world population by increasing crop yields by more than 30%, suppressing weeds, and improving soil water and heat conditions. Polyethylene is the primary raw material for mulch film, but biodegradable mulch film has also been widely used recently. The residual plastic film in the environment will break into fragments, ultimately forming microplastics (MPs). Microplastics in soil ecosystems disrupt soil aggregate structure, alter microbial community composition, interfere with the growth of soil flora and fauna, perturb biogeochemical cycling of essential elements, and ultimately threaten human health through environmental exposure or food chain transmission, therefore, their are defined as emerging pollutants. Microplastics in terrestrial ecosystems are C-rich substances of anthropogenic origin. As MPs age, they release dissolved organic matter (e.g., polymer fragments, additives, oligomers, monomers) into the soil environment. Therefore, elucidating the aging behavior of mulch film-derived MPs in farmland soils and their influence on SOC pools is important for accurately assessing soil carbon sinks.

Microplastics are emerging pollutants that may affect soil organic carbon (SOC) and thus influence global change. However, the aging behavior of mulch film-derived MPs exposure to farmland soils and their impact mechanisms on microbial necromass carbon (MNC) formation remain poorly understood. Polyethylene (PE) and biodegradable (Bio, polypropylene carbonate and polybutylene adipate terephthalate synthetic material (PPC+PBAT)) mulch film-derived MPs at 0.2% (w/w) dosages were mixed into farmland soils, incubated for 120 days and sampled every 30 days. On day 120, compared to MPs before incubation, the relative contents of C–H or C–C on the surfaces of PE-MPs and Bio-MPs decreased by 12.2% and 3.7%. In the first 60 days, compared to control soils (CK), the bacterial necromass carbon (BNC) content decreased by 54.0–56.0% and 23.9–44.8%, while the MNC decreased by 30.2–53.8% and 11.8–23.0% in farmland soils exposed to PE-MPs and Bio-MPs, respectively ($p<0.05$). This reduction was attributed to the rapid turnover of necromass. During 90–120 days, under PE-MPs and Bio-MPs exposure, the contents of microbial biomass carbon (MBC) (66–76% and 10–18%), dissolved organic carbon (DOC) (1.8–16.9% and 12.4–26.4%), MNC (8.2–29.2% and 14.0–16.1%), and SOC (10.7–11.0% and 6.8–8.9%) showed significantly higher levels than those in the CK treatment. The PE-MPs and Bio-MPs promoted an increase in MNC and SOC content, which was associated with MPs aging that altered available nutrients and enzyme activities and directly or indirectly promoted an increase in DOC and microbial biomass. In summary, mulch film-derived MPs affect MNC accumulation and SOC sequestration, especially conventional PE-MPs.

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# Shifts in C-degradation genes and microbial metabolic activity with vegetation types affected the surface soil organic carbon pool

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## ABSTRACT

The incorporation of plant-derived biomass by microorganisms into deceased microbial biomass, i.e., a "microbial carbon pump", is essential for forming a soil carbon (C) pool. Therefore, microbial communities and associated functions could shape the formation of soil organic C (SOC) composition and persistence. However, the mechanism by which microorganisms mediate the degradation of various types of biomass (such as plant or microbial) and its impact on SOC formation under different vegetation types remains unclear. Herein, we analyzed microbial communities, carbohydrate-activated enzymes (CAZymes), absolute quantification of C- degradation genes, and extracellular enzyme activities to track microbial-mediated SOC formation under three vegetation types on the Loess Plateau. Changes in vegetation type influenced microbial community structure and distributions of certain bacterial groups. Specifically, dominant bacterial taxa shifted from oligotrophic Actinobacteria to eutrophic Proteobacteria from grass to forest soil. The proportion of microbial CAZymes responsible for decomposing plant-derived components (86–89%) exceeded that of microbial-derived components (11–14%), suggesting a greater capacity for the degradation of deceased plant biomass by microorganisms. There was a reduction of 14%–17% in the absolute abundance of specific C-degradation genes for hemicellulose and cellulose in forest soil compared to grass, while an increase of 20%–32% was observed in lignin and chitin degradation. This indicated a higher decomposition potential of lignin and chitin by microorganisms in forest soil. The number of CAZymes genes involved in the degradation of bacteria-derived biomass (peptidoglycan) was higher than fungi-derived biomass (chitin and glucans) and had a close correlation with the $qCO_2$, microbial biomass C (MBC), and particulate organic C (POC). The abundance of C-degrading genes increased with the increase in the corresponding enzyme activity, indicating that enzyme activity is regulated by functional genes. In conclusion, shifts in CAZymes genes encoding for the degradation of diverse carbon sources could impact microbial metabolic activity through a microbial "carbon pump" regulation process. This mechanism could facilitate the formation of soil organic carbon and its fractions across different vegetation types.

# Drivers and Consequences of Microbial-Derived Carbon Loss in Degraded Alpine Grasslands on the Qinghai-Xizang Plateau

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## ABSTRACT

Soil organic carbon (SOC) and its microbial-derived C are severely reduced in degraded alpine grasslands on the Qinghai-Xizang Plateau, a region highly sensitive to climate change. Acting as relatively stable microbial metabolic products, microbial necromass carbon (MNC), extracellular polymeric substances carbon (EPSC), and glomalin-related soil proteins (GRSP) serve as key components of the SOC pool. However, their roles in degraded alpine grassland remain poorly understood. We quantified MNC, EPSC, and total GRSP across alpine grassland representing different degradation stages (non-degradation, light degradation, moderate degradation, and heavy degradation) and assessed their contributions to SOC along with controlling factors. Our results showed that although absolute contents of MNC, EPSC, and total GRSP declined significantly with increasing degradation (0.75–27.59 mg $g^{-1}$, 1.00–3.07 mg $g^{-1}$, and 0.40–13.89 mg $g^{-1}$, respectively), the relative contributions of MNC and T-GRSP to SOC remained stable, whereas the contribution of EPSC increased. Notably, MNC contributed substantially more to SOC than EPSC and GRSP (1.80%–68.34% vs. 1.37%-22.77% and 2.90%–26.48%). The absolute loss of MNC during SOC decline was 70.6 and 1.3 times as great as that of EPSC and total GRSP, respectively. Further analysis indicated that microbial respiratory entropy affected by physicochemical properties and microbial biomass was a key driver of MNC accumulation relative to EPSC. In summary, microbial metabolites are fundamental to SOC persistence, underscoring their critical role in mitigating degradation and guiding sustainable management of alpine grassland.

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# Fungal Necromass Carbon: Insights into Global Soil Carbon Sequestration and Its Practical Implementation in Circular Agricultural Systems

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## ABSTRACT

Fungal necromass carbon (FNC) is a quantitatively significant and chemically recalcitrant component of stable soil organic carbon (SOC), yet its global distribution, mechanistic controls, and deliberate manipulation in agro-ecosystems remain under-characterized. Here we integrate two complementary studies that (i) resolve the biogeochemical drivers of FNC storage across major croplands and (ii) translate this knowledge into a scalable circular-agriculture technology that actively manages FNC for concurrent C sequestration, waste valorization, and crop-quality gains.

Meta-analysis of 873 topsoil samples (0–20 cm) from 124 sites across Asia, Europe and North America showed FNC averages 25.1 ± 0.6 % of SOC (range 18–34 %). Density declined: North America 8.39 g $kg^{-1}$ (25.6 %) > Asia 5.56 g $kg^{-1}$ (25.1 %) > Europe 3.94 g $kg^{-1}$ (20.3 %). Sixty-seven percent of variance was explained by three mechanisms: (1) hyphal enmeshment promoting aggregate occlusion; (2) melanin and chitin (10–15 % of dry mass) with residence times 3.4 × bulk SOC; (3) biomass input linked directly to microbial biomass C (MBC; path coefficient 0.32, $p < 0.01$). pH, clay and total N indirectly influenced FNC via MBC ($R^2 = 0.33$). Conservation practices amplified these drivers: no/reduced tillage raised FNC efficiency by 45 % and straw return increased FNC by 26 %, supplying 36 % of SOC gain under reduced tillage.

We translated these insights into a Livestock–Crop–Mushroom (LCM) biorefinery. Cattle manure (C/N 16) and straw (C/N 65) were co-composted into lignocellulosic substrate (St), colonised by *Stropharia rugosoannulata*. Fruiting bodies yielded 1.8 kg mycoprotein $m^{-2}$; spent substrate (SMS) containing 286 mg C $g^{-1}$, 23.3 mg N $g^{-1}$, 8.7 % chitin and 2.1 % melanin was pelletised as biofertilizer (StM). In oat field trials StM boosted grain crude protein by 5.1 % ($p < 0.05$), root biomass by 6.5 % and forage yield by ~20 % versus unfertilised soil, outperforming St. Thermophilic composting plus fungal metabolism cut antibiotic resistance genes by 46 %, pathogens by 25 % and oxytetracycline residues by 68 % (3232 → 630 µg $kg^{-1}$), delivering simultaneous gains in C storage, productivity and ecological safety.

Collectively, FNC is a quantifiable, manageable reservoir connecting soil C cycling with circular agriculture. Global data identify management levers (reduced tillage, residue retention) to maximise FNC, while LCM provides a farm-scale technology to engineer fungal C inputs, close nutrient loops and upgrade wastes. In the future, research priorities could focus on three key directions: (i) select fungi with high chitin/melanin for longer C persistence; (ii) scale LCM to cereals and contrasting climates; (iii) embed FNC modules in Earth-system models. By highlighting fungi as both inherent C stocks and deployable tools, this work advances fungal-centric strategies for climate-resilient and sustainable intensification of agricultural systems.

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# The influence and mechanism of the interaction between Mineral-associated Organic Carbon and soil aggregates on soil carbon sequestration

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**ABSTRACT**

Mineral-associated Organic Carbon (MAOC) serves as a key component for maintaining long-term carbon stability in soil, with its dynamic interactions with soil aggregates profoundly influencing soil carbon sequestration. To investigate the distribution patterns of MAOC across aggregate sizes and their synergistic stabilization mechanisms, the research systematically analyzes the formation processes of soil organic carbon and soil aggregates, highlights MAOC's distribution characteristics in different aggregate sizes, examines aggregates' physical protection effects on MAOC and evaluates MAOC's feedback contributions during aggregate formation. Results revealed that the MAOC content in the 0-20 cm soil layer of Cropland（Cr） was significantly lower than that in natural grassland（NaG）. MAOC exhibited greater stability in the 20-40cm soil layer, particularly in 1-2mm and 3-5mm soil aggregate sizes. This indicates that MAOC plays a crucial role in deep soil carbon sequestration, with its stable accumulation closely linked to aggregate structure. Through a synergistic mechanism of physical isolation and chemical adsorption, both factors jointly enhance the stability of soil carbon reservoirs.By exploring the MAOC-aggregate feedback relationship, this research elucidates their crucial role in soil carbon stabilization, providing theoretical foundations for understanding soil carbon sequestration mechanisms.

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# Orchard soils exhibit the highest microbial $CO_2$ fixation potential and contribution to soil organic carbon across land-use types in Qaidam Basin

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**ABSTRACT**

Soil organic carbon content varies across different land-use types. Elucidating $CO_2$-fixing microorganisms and their fixation potential is pivotal for accurately evaluating and improving soil carbon sinks and enriching the theory of microbial carbon sequestration. However, the $CO_2$ fixation potential, driving factors and mechanism of soil $CO_2$-fixing microorganisms in different land-use types are still unclear. This study investigated the $CO_2$ fixation potential (CFP) and sequestration mechanism in 0-10 cm topsoil (36 soil samples) of typical grassland (GL), facility farmland (FAL), farmland (FL) and orchard (OD) in the Qaidam Basin by $^{13}CO_2$ isotope tracer incubation method (61 d), metagenomic sequencing and partial least squares method. The $^{13}CO_2$-fixing rates (26.7 mg $^{13}C$ $m^{-2}$ $d^{-1}$) in OD were 2.26, 1.24 and 1.31 times those of GL, FAL and FL, respectively ($p < 0.05$). Correspondingly, 160 unique $CO_2$-fixing species were observed in OD, mainly including *methanogenic archaeon* ISO4-H5, *Leptospira alstonii*, Candidatus *Saccharibacteria* bacterium GW2011 GWA2 46 10 and *Bacillus encimensis*, with few unique species in other soils. GL showed higher relative abundances of the Calvin (8.78%) and C4-Dicarboxylic acid (3.89%) cycles ($p < 0.05$). CFP was directly affected by metabolic pathways and soil properties, and indirectly by microbial communities ($p < 0.05$), with ammonium ion, total nitrogen, and particulate organic carbon as key determinants. In conclusion, CFP can be improved by regulating soil physical-chemical factors. Our findings clarify the structural and functional variations of $CO_2$-fixing microbial communities across land uses, offering theoretical support for exploring novel $CO_2$-fixing microbes and optimizing $CO_2$ fixation capacity.

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# Community, metabolic pathways and fixation potential of soil $CO_2$-fixing microorganisms on the Loess Plateau

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## ABSTRACT

Soil $CO_2$-fixing microorganisms (CFMs) convert $CO_2$ into soil organic carbon (SOC) via light or chemical energy, acting as core drivers of terrestrial carbon sequestration and critical for mitigating climate change and achieving carbon neutrality. However, their community assembly rules, metabolic differentiation mechanisms and contribution thresholds to SOC accumulation under natural environmental changes remain unclear. To address these gaps, this study integrated molecular biology techniques, $^{13}CO_2$ labeling and microbial isolation to systematically explore CFMs community structure, metabolic pathways and fixation potential across precipitation gradients and vegetation types on the Chinese Loess Plateau.

CFMs communities exhibited distinct spatial heterogeneity shaped by environmental factors and geographic distance: *cbbL*-harboring CFMs (dominated by *Proteobacteria* and *Actinobacteria*) prevailed in the southern Plateau, while *cbbM*-harboring taxa (primarily *Alphaproteobacteria*) dominated the north. Precipitation and vegetation jointly drove CFMs functional differentiation: fixation potential increased with precipitation (semi-arid $^{13}$C-SOC was 3.9 times higher than arid regions), with arid soils relying on the Calvin cycle (dominant genus: *Rubrobacter*) and semi-arid soils on Reductive citrate (rTCA) cycle and 3-Hydroxypropionate bi-cycle (dominant genus: *Bradyrhizobium*). Grasslands outperformed shrublands and forests in sequestration capacity (47% and 93% higher $CO_2$-fixing gene abundance), with *Rubrobacter*, *Solirubrobacter*, *Conexibacter* and *Streptomyces* as key taxa, and relied on the Calvin cycle—contrasting with forests' rTCA-dominated fixation.

Notably, CFMs showed preferential carbon allocation to mineral-associated organic carbon ($^{13}$C-MAOC, 49.3%–70.1%), particulate organic carbon ($^{13}$C-POC, 2.5%–15.9%) and microbial biomass carbon ($^{13}$C-MBC, 1.5%–18.8%), with dissolved organic carbon ($^{13}$C-DOC) accounting for only 0.3%–1.2% of $^{13}$C-SOC. Gram-negative bacteria dominated fixation (44.6%–65.6%) with strengthening dominance over time, and fixed $CO_2$ was primarily incorporated into SOC as bacterial necromass. Precipitation and vegetation indirectly regulated fixation potential via modifying soil nutrients and CFMs communities. Nine strains were isolated from grasslands, with *Agrobacterium* sp. A4 and *Brevundimonas vesicularis* sp. A7 showing the highest $CO_2$ fixation efficiency (4.2 and 4.1 mg/L, respectively).

Overall, CFMs display diverse community and metabolic adaptations to precipitation and vegetation changes, with a fixation rate of 8.1–27.0 mg $^{13}C\ m^{-2}\ d^{-1}$ and bacterial necromass as a stable SOC component. These findings clarify the linkages between environmental factors, CFMs traits and carbon sequestration, providing a scientific basis for optimizing soil management to enhance terrestrial carbon sinks.

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# Linking the diversity of soil $CO_2$-fixing microorganisms with soil organic carbon accumulation along biological soil crust chronosequence

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## ABSTRACT

Microbial $CO_2$ fixation constitutes a pivotal route for soil organic carbon (SOC) formation, particularly in low-productivity ecosystems such as biocrusts. Yet, it remains unclear how microbial $CO_2$ fixation rate and the diversity of $CO_2$-fixing taxa and genes respond to biocrust succession, limiting our ability to assess biocrusts role in global C budgets. Here, we quantified the contribution of $CO_2$-fixing microbes to SOC formation across biocrust successional stages using $^{13}CO_2$ labeling, high-throughput sequencing, and absolute quantification of $CO_2$-fixation genes. Biocrust development substantially restructured $CO_2$-fixing microbial communities, increasing their ACE diversity index by 160–200%. This diversification coincided with pronounced increases in microbial $CO_2$ fixation rates, as indicated by $\delta^{13}C$ enrichment rising by 34%, 68%, and 810% in the biocrust, 0–2 cm, and 2–10 cm soil horizons, respectively, relative to bare sand. Across soil horizons, microbial $CO_2$ fixation peaked in the biocrust (16–21 g C $m^{-2}$ $yr^{-1}$), exceeding that of the 0–2 cm and 2–10 cm horizons by 4.5–6.4 and ~15 fold, respectively. Enhanced $CO_2$ assimilation correlated more with community diversity than with gene abundance, suggesting that community-level organization, rather than individual genetic capacity, drives fixation efficiency. This community restructuring and its enhanced function were supported by improved nutrient availability during biocrust succession. Correlations between $^{13}C$-SOC, dissolved nitrogen, and leucine aminopeptidase activity point to nitrogen-mediated facilitation, while co-variation between $^{13}C$-SOC, mineral associated organic C, and clay content indicates mineral association as a key stabilization pathway. In summary, biocrust succession accelerates microbial $CO_2$ fixation and SOC buildup mainly via increased fixer diversity, with clay and nitrogen jointly governing C sequestration and stabilization processes. With their 0.35 Pg C yr-1 sequestration capacity, biocrust autotrophs represent an overlooked nature-based solution, targeted restoration can amplify dryland C storage potential while buffering against climate variability.

**Key words:** $CO_2$ fixing microorganisms; $CO_2$ fixation genes; $^{13}CO_2$ labeling; soil organic carbon formation; biocrusts

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# Stability of Soil Organic Carbon and Shifts in Microbial Community Structure along Vegetation Succession in the Shrinking Area of Plateau Inland Lake

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## ABSTRACT

Climate change and human activities threaten lakes in arid regions with shrinkage and drive soil salinization, thereby compromising regional ecological security. Land degradation and ecological restoration in contracting lake areas have garnered increasing research attention. In this study, we examined changes in soil organic carbon (SOC) content and microbial community diversity under various vegetation restoration strategies—Carex (CL), Salicornia (SL), Tamarisk (TL), reed (RL), and grass (GL)—along the lakeshore of Dalinor Lake in Inner Mongolia. Results indicated that all restoration measures enhanced SOC content and increased the proportion of the more stable mineral-associated organic carbon (MAOC), and GL restoration resulted in the highest SOC storage and stability. High-throughput sequencing revealed that the proportions of plant-derived carbon (PlantC) and microbial-derived carbon (MicroC) in soil increased markedly during vegetation succession, from 6.6% and 25.77% to 43.78% and 42.88%, respectively. Vegetation restoration also stimulated microbial activity, as reflected by elevated levels of microbial biomass carbon (MBC), fungal-derived carbon (Fungal-C), and bacterial-derived carbon (Bacterial-C), with GL restoration notably enhancing Fungal-C. Compared to bare land (BL), restored sites showed increased soil microbial α-diversity (higher Chao1 and Shannon indices), though the Simpson index remained largely unaffected. In early succession, bacterial phyla such as Balneolota and Gemmatimonadota were dominant, whereas Acidobacteriota and Actinomycetota prevailed in mid-to-late stages that crucial for ameliorating degraded saline-alkali soils and metabolizing organic compounds. Redundancy analysis (RDA) indicated that soil available phosphorus (AP), available potassium (AK), pH, and total dissolved solids (TDS) were the primary factors shaping microbial diversity and composition in early succession, while SOC content and composition became dominant in later stages. Mantel test analysis further highlighted significant influences of pH, TDS, TN, CEC, SOC, C/N ratio, microbial diversity indices, and dominant bacterial phyla on both PlantC and MicroC. Structural equation modeling (SEM) demonstrated that MicroC was predominantly driven by biodiversity and bacterial phyla, whereas the composition of SOC directly regulated PlantC accumulation. Successional vegetation communities indirectly influenced soil organic carbon partly by modifying soil physicochemical properties, microbial diversity, and community composition, ultimately governing PlantC and MicroC dynamics. Collectively, this collaborative study between Chinese and Norwegian partners provides valuable insights for future adaptive management of climate change risks and SOC sequestration strategies in arid lake systems experiencing shrinkage.

**Keywords:** Soil organic carbon; Vegetation restoration; Microbial community diversity; Arid inland lake; Carbon components; Ecological succession.

# Quantifying microbial controls on particulate and mineral-associated organic matter in cropland soils

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**ABSTRACT**

Soil organic matter (SOM) is essential for maintaining soil fertility and sustainable agriculture. It is commonly fractionated into particulate (POM) and mineral-associated organic matter (MAOM) fractions, which differ in stability and microbial regulation. However, the specific microbial traits that regulate these fractions across large spatial gradients remain poorly understood, constraining our ability to manage SOM effectively. Here, we combined size-based SOM fractionation and amplicon sequencing of 444 cropland soils derived mainly from loamy and silt loam substrates under dominant maize and rice cultivation in Liaoning province, northeast China with a global meta-analysis (2438 observations) to disentangle microbial controls on POM and MAOM. Microbial biomass was quantified from microbial biomass carbon and nitrogen, whereas necromass was estimated from amino sugar biomarkers, revealing that microbial biomass was positively associated with both fractions, while necromass strongly predict MAOM. Microbial diversity and network influenced SOM fractions indirectly by shaping biomass and necromass, and microbial traits collectively explained up to 24% of POM and 62% of MAOM variation. These findings were corroborated by global evidence, highlighting the generality of microbial controls across ecosystems and scales. Our study provides a mechanistic framework for integrating microbial processes into SOM management and carbon stabilization strategies at landscape scales.

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# Activation Energy of Soil Organic Matter Decomposition and Consequences of Global Warming

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Activation energy (Ea) of (bio)chemical reactions – the fundamental parameter, defining the reaction rates – has never been critically evaluated and generalized for processes of organic matter transformations in soil. Based on the database of Ea for a broad range of i) oxidative and hydrolytic exoenzyme activities, ii) $CO_2$ production and iii) heat release during soil incubation, as well as iv) thermal decomposition of soil organic matter (SOM), we assessed the Ea for processes of SOM transformation. After a short description of the four approaches to assess Ea of SOM transformation – all based on the Arrhenius equation – we present the Ea of chemical (79 kJ $mol^{-1}$) and microbial (67 kJ $mol^{-1}$) mineralization, microbial decomposition (40 kJ $mol^{-1}$), and exoenzyme-catalyzed depolymerization (33 kJ $mol^{-1}$) of SOM. The catalyzing effects of exoenzymes reduce the energy barrier of SOM decomposition by more than twice that of its chemical oxidation (from 79 to 33 kJ $mol^{-1}$). The Ea of exoenzymatic hydrolysis of N-, P-, and S-containing organic compounds is about 9 kJ $mol^{-1}$ lower (40-fold faster reactions) than that of other (N-, P-, and S-free) organic substances. Under real soil conditions (not in suspension as in enzyme activity analysis), where organic substrates are physically protected and exoenzymes are partly deactivated, microbial mineralization of SOM is 140-fold faster compared to its chemical oxidation. The Ea of microbial mineralization of SOM increases from biochemically labile to stable pools. This is one of the reasons for the decrease in the $CO_2$ efflux from soil during long-term incubations.

Since processes with higher Ea are more sensitive to temperature increase, global warming will stimulate faster decomposition of stable organic compounds and accelerate the C cycle much stronger than the cycling of the nutrients N, P, and S. The consequence will be a shift in the stoichiometric ratios of microbially utilized substrates. Overall, Ea is an easily measurable crucial parameter of (bio)chemical transformations of organic matter in soil, enabling the assessment of process rates and the inherent stability of SOM pools, as well as their responses to global warming.

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# Microbial Intracellular Carbon Storage: A Missing Link in Global Soil Carbon Sequestration Framework

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## ABSTRACT

Exploring carbon use efficiency for soil C sequestration has been focused on microbial growth and respiration. Fungi and bacteria can divert assimilated C into intracellular storage, thus reducing unnecessary C respiration loss to $CO_2$. However, intracellular C storage (accumulation of neutral lipids) as a pathway for transforming crop residue-C into soil organic C (SOC) has been neglected. As one of the first researchers to test the hypothesis, we collected soil samples in 2025 in western Illinois, USA in an experiment with four treatments: municipal biosolids, vegetative compost, grass restoration, and chemical fertilizer. Biosolids (byproduct of microbial processing of wastewater treatment) and vegetive compost (windrow-composting and curing of grass clipping and food scraps) were applied in 2013 at 8% the top 15-cm soil weight. Corn was planted annually. Grass restoration was established by converting cropland to natural regrowth. Sample analysis was conducted using standard phospholipids fatty acid (PLFA) method involving total lipid extraction, separation using silica gel column, derivatization to fatty acid methyl esters, and measurement by gas chromatography for neutral lipid fatty acid (NLFA) and PLFA. Higher NLFA amount and NLFA/PLFA ratio were found in biosolids-amended soil (81.9 nmols $g^{-1}$ and 1.88), grass restoration (81.3 nmols $g^{-1}$ and 1.24), and compost-amended soil (64.2 nmols $g^{-1}$ and 1.35) than chemical fertilizer control (50.5 nmols $g^{-1}$ and 1.17). Upon microbial turnover, neutral lipids became stable soil organic matter directly or through association with clay minerals, leading to high annual soil C sequestration (SOC gain excluding residual biosolids C) at 0.42 Mg $ha^{-1}$in biosolids-amended soil, which doubles the goal of international “4 per 1000” initiative. Annual soil C sequestration was 0.09 Mg $ha^{-1}$ in conventional fertilizer soil, 0.14 Mg $ha^{-1}$ in compost-amended soil, and 0.39 Mg $ha^{-1}$ under grass restoration. Addition of biosolids created organic nutrients and moisture-rich microhabitat that could support cells to thrive in variable or harsh agricultural environments, allocating more assimilated C to storage as K-strategy microorganisms. The soil C sequestration rate was correlated to NLFA (microbial C storage) and NLFA/PLFA ratio rather than PLFA (microbial structure biomass). The significance of our findings is that future management for soil C sequestration should focus on improving soil environment conditions by amending soil with long-lasting, labile and non-labile balanced organic nutrients to stimulate microbial intracellular C storage.

# Grassland degradation-induced soil organic carbon loss associated with micro-food web simplification

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**ABSTRACT**

Soil micro-food webs play a vital role in sustaining soil carbon cycling and stocks through the activities and interactions of individual organisms. However, grassland degradation disrupts these micro-food webs and is expected to reduce soil carbon stocks. This hypothesis was tested along degradation transects that were established in alpine meadows and steppes in arid regions, examining how multitrophic organisms and microbial metabolic efficiency respond to grassland degradation and how these responses relate to soil organic carbon (SOC). Grassland degradation reduced microbial necromass accumulation coefficient (the ratio of microbial necromass carbon to microbial biomass carbon) and increased microbial metabolic quotient (the ratio of soil respiration rate to microbial biomass carbon), indicating that microbes may prioritize SOC decomposition for resource acquisition over growth and necromass accumulation. Degradation led to increased bacterial and fungal diversity, reduced protist and nematode diversity, and simplified the structure of micro-food web (network complexity). Overall, grassland degradation reduced microbial metabolic efficiency, linked to reduced plant biomass, lower soil clay content, and a simplified micro-food web—particularly weakening interactions among microbes, microbivores, and predators—which is associated with SOC loss in degraded grasslands. These findings indicate the necessity of maintaining micro-food web structures to promote soil carbon sequestration in degraded grasslands.

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# Long-term fate of photosynthetic carbon in desert plants: microbial necromass-driven pathways for soil carbon stabilization

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**ABSTRACT**

As a core component of the terrestrial carbon (C) cycle, plant photosynthetic C assimilation regulates soil organic carbon (SOC) sequestration. However, the allocation patterns of photosynthetic C across different soil layers in desert ecosystems remain unclear. Through in situ field $^{13}CO_2$ pulse labeling applied to Alhagi sparsifolia, a keystone desert species, we traced photosynthetic C dynamics over 360 days. This included vertical translocation from plant aboveground to belowground systems (0-30, 30-60, 60-100, and 100-200 cm depths) and subsequent partitioning into SOC, soil microbial biomass (phospholipid fatty acid), microbial necromass (amino sugars), and plant residue (lignin phenols). Over time post-labeling, $^{13}C$ in plants gradually shifted from aboveground to belowground biomass. Although plant residue $^{13}C$ accumulated gradually in the soil, its contribution to SOC was only 0.2%–1.1%, lower than that of microbial necromass (12%–30%). In the 0–100 cm soil layer, microbial necromass $^{13}C$ and its contribution to SOC increased initially and then stabilized over time, while it continued to increase at 100–200 cm depth. Microbial necromass $^{13}C$ dynamics were more strongly associated with SOC than plant residue. In desert ecosystems, microbes are the primary contributors to deep SOC accumulation, more than in surface layers.

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# Role of microbial-derived carbon to soil organic carbon formation during natural and artificial vegetation restoration

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**ABSTRACT**

Microbial-derived carbon are the important sources of soil organic carbon (SOC) formation. Particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) are two physical components of SOC. Their protection mechanisms, mean residence time, biogeochemical properties are different because of distinctive sources, which can be better described in aspects of soil carbon accrual, persistence as well as function. Previous study showed that there is difference in SOC accumulation processes between forestland and grassland. However, it remains unknown how do microbial necromass work during SOC accumulation, especially in the formation of POC and MAOC in forestland and grassland. Therefore, we selected artificial forestland and natural grassland on the Loess Plateau in China, by biomarkers (amino sugar) to exploring contributions of microbial-derived carbon to POC and MAOC in natural grassland and artificial forestland, as well as influencing factors. Results showed that accumulation of POC and MAOC in forestland were different from grassland at 0-60 cm soil layers. At 0-60cm soil layer, contribution of MAOC to SOC (73.7%) in natural grassland were higher than that (70.7%) in artificial forestland. However, contribution of POC to SOC (26.6%) in natural grassland were lower than that (29.3%) in artificial forestland at 0-60 cm soil layer. Microbial necromass carbon (MNC) contents in POC were higher than that in MAOC at 0-60 cm soil layer in artificial forestland and natural grassland. MNC contents in POC under artificial forestland was higher than that of natural grassland. MNC in MAOC contents under natural grassland was higher than that of artificial forestland at 0-20 cm soil layer, but lower than that of artificial forestland at 20-60 cm soil layer. These results suggested that vegetation restoration could promote MAOC accumulation and contribute to SOC sequestration, especially natural grassland restoration. These conclusions are significant to know about the mechanism of soil organic carbon formation and accumulation during the artificial and natural vegetation restoration.

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# Exploring drivers of microbial drought sensitivity through combined laboratory and field approaches

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## ABSTRACT

Predicting how soil microbial communities respond to drought is a major challenge in terrestrial ecology, especially in heterogeneous landscapes where soils differ in texture, nutrient status, and climatic history. In this study, we combined a controlled laboratory incubation with a coordinated field drought experiment to explore whether background site characteristics and laboratory moisture–response curves can help anticipate ecosystem responses to reduced precipitation. We collected soils from six grassland sites across Italy spanning a broad gradient of pedoclimatic conditions and characterised their microbial and nutrient dynamics under varying levels of water availability.

In the laboratory, soils were incubated at five water-holding capacity (WHC) levels (10–80%) to establish moisture–response functions for a suite of microbial processes. We quantified microbial respiration, microbial biomass C, N and P, microbial growth via $^{18}$O-DNA incorporation, dissolved organic and inorganic nutrients (including dissolved P), and the activities of eight extracellular enzymes involved in C-, N- and P-cycling. These datasets provided site-specific profiles of microbial sensitivity and functional potential across a moisture gradient.

To assess whether these laboratory-derived patterns align with field drought behaviour, an *in-situ* rain-exclusion experiment was carried out in each grassland, imposing a 2.5-month drought during the plant growing season. The same microbial and nutrient variables were measured in the field following drought, enabling a comparison between controlled moisture–response curves and in situ functional responses.

Although data analysis is ongoing, preliminary results point to systematic links between background soil properties, laboratory moisture sensitivity, and field drought outcomes. Relationships appear to be process - dependent, suggesting that some microbial functions may be more predictable from laboratory assays and site characteristics than others. By integrating both laboratory and field manipulations, this work aims to develop a mechanistic and empirically grounded framework for assessing drought impacts on soil microbial communities.

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# Global Change Reshapes Microbial Residues and Plant Lignin Components in Soils

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**ABSTRACT**

Microbial- and plant-derived carbons are critical sources of soil organic carbon (SOC), but the specific responses of soil amino sugars and lignin phenols to global change remain unclear. In this study, we conducted 3193 observations across 553 experiments aimed at investigating the potential role of amino sugars and lignin phenols in maintaining SOC accumulation in response to land-use change, nutrient additions, elevated C dioxide ($eCO_2$), warming, and drought. The results showed that land restoration increased amino sugars (35.1%), glucosamine (53.8%), galactosamine (68.6%), muramic acid (33%), lignin phenols (79.3%), and vanillyl phenols (68%), whereas land degradation reduced these compounds, including syringyl. Nitrogen (N) and phosphorus (P) additions enhanced amino sugar, glucosamine, and muramic acid contents, whereas P addition selectively increased glucosamine content. N, P, and potassium additions increased glucosamine (16.8%), galactosamine (17.3%), muramic acid (21.6%), and lignin phenol (4.8%) contents, while $eCO_2$ only increased amino sugar content by 14.6%. Warming increased glucosamine and muramic acid contents, whereas drought had no effect on amino sugar and lignin phenol contents. Soil amino sugars played a more critical role than lignin phenols in SOC accumulation, and their dynamics were influenced by soil nutrient availability and microbial communities under global change. These findings advanced our understanding of the dominant role of microbial residues in SOC accumulation mediated by the nutrient stoichiometry and microbial communities.




**Figure 1**. A world map showing the distribution of ecosystems included in this meta-analysis. Different ecosystem types are represented by different colors, and the sizes of the circles indicate sample sizes.



**Figure 2.** Response ratios of global change factors (GCFs) on the contents of total amino sugars (TAS, a), glucosamine (Glu, b), galactosamine (Gal, c), muramic acid (Mur, d), lignin phenols (VSC, e), vanillyl (VP, f), syringyl (SP, g), and cinnamyl (CP, h). Weighted means and their 95% confidence intervals of response ratios (RRs) are provided. LD, land degradation; LR, land restoration; N, nitrogen addition; P, phosphorus addition; NP, nitrogen phosphorus fertilizer addition; NPK, nitrogen phosphorus potassium fertilizer addition, $eCO_2$, elevated carbon dioxide. The open and closed symbols indicate nonsignificant ($p > 0.05$) and significant ($p < 0.05$) effects, respectively. The numbers on the below side of the means represent the sample size.

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# Turnover of microbial biomass residues to soil organic matter and its contribution mechanism

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## ABSTRACT

Microbial biomass residues have been recognized as significant material contributors to the formation of SOM. However, the turnover of microbial biomass residues with respect to their detailed microbial food web and the mechanism by which material from microbial sources is sequestered in soil organic matter still remains elusive. Here, we setup a laboratory incubation experiment by introducing $^{13}$C-labeled microbial biomass ($^{13}$C-labelled bacterial and fungal biomass residues separately) into the soil. We tracked microbial biomass C through the microbial food web over time using the concentrations and isotopic compositions of biomarker PLFA, and tracked $^{13}$C-amino sugars (from chitin and peptidoglycan) and amino acids (from proteins) in order to shed light onto the mechanism of microbial derived C to SOM. We observed that after 120 days, 46.5% of the bacterial-derived $^{13}$C remained in the soil, compared to 56.55% of the fungal-derived $^{13}$C after 240 days. Combined with the half-life results for the fast and slow decomposition pools of both C sources further confirmed that fungal-derived C is relatively more stable than its bacterial-derived C. We found the PLFA patterns over time demonstrate the pathway of $^{13}$C transformation associated with different groups of microorganisms along the incubation. Specifically, bacterial-derived $^{13}$C was utilized by fungi first, then the label was shifted from fungi to Gram$^+$ bacteria, AMF, actinomycetes; the fungal-derived $^{13}$C was initially assimilated by Gram$^-$ bacteria, followed by sequential transfer to fungi, Gram$^+$ bacteria, AMF, actinomycetes. We also observed the ratio of $^{13}$C-fungal derived glucosamine to $^{13}$C-muramic acid significantly increased before day 14, then levelled off until the end of the experiment in the bacterial-derived $^{13}$C treatment. This further highlighted that bacterial C was stabilized in soil by conversion to fungal biomass that grew on the bacterial biomass. In the fungal-derived $^{13}$C treatment, although fungal-derived $^{13}$C was rapidly decomposed in the early stage of incubation, it re-accumulated later, with the isotopically labeled fungal C ultimately retained in the soil as fungal residues. This indicates that, by the end of the incubation, C-regardless of whether it originated from bacterial or fungal biomass-was ultimately stabilized primarily as fungal necromass. Interestingly, in the bacterial-derived $^{13}$C treatment, the shifts in $^{13}$C-amino acids distribution pattern reflect three phases of the central metabolism. Finally, themetabolism slowed down and thus the TCA cycle was less active and C rather than energy was preserved may thus be an important pathway for soil organic C sequestration in soil. In summary, our study traced the detailed turnover pathways of microbially derived C, elucidated the mechanisms by which this C contributes to soil C stabilization, and provided a scientific basis for a holistic understanding of microbially mediated C cycling processes.

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# Stoichiometric steering of microbial necromass–mineral coupling drives Technosol genesis in iron mine tailings

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## ABSTRACT

Transforming mine tailings into functional soils requires persistent organic carbon accumulation, yet conventional amendments fail because they prioritize carbon quantity over mineral compatibility. We hypothesize that substrate stoichiometry can steer microbial community composition toward producing necromass chemically optimized for stabilization by reactive mineral surfaces—a stoichiometry–microbiome–mineral (SMM) cascade. Using iron ore tailings as a pedogenic blank slate, we compared low-C:N (alfalfa, ~15) versus high-C:N (maize straw, ~60) amendments under a pioneer grass, tracking mineral weathering, aggregate formation, and necromass fate via amino-sugar biomarkers, NanoSIMS imaging, and Fe K-edge XAFS. Low C/N ratio organic matter input (alfalfa meal) increased the proportion of large aggregates by 8.3% and reduced the C/N ratio of microaggregate-related organic matter to 8.87, indicating selective stabilization of nitrogen-rich microbial compounds. Low-C:N input shifted microbial communities toward bacterial dominance, increasing bacterial necromass accumulation by 8.5% relative to fungal residues. High C/N ratio modifiers (corn stalks) primarily increased the unstable particulate organic matter library without corresponding mineral transformation. NanoSIMS imaging provided direct spatial evidence that microbial-derived carbon (characterized by a high $^{14}N^{-}/^{12}C^{-}$ ratio) preferentially binds to Fe and Al hydroxyl oxide particles rather than existing in pore spaces. This molecular-scale co-localization occurred against a mineral background dominated by goethite (~42%) and ferrihydrite (~18%), confirming ligand exchange and surface complexation as the main retention mechanisms. Our results establish a "metabolic matching" principle: engineering soil genesis from mineral waste requires stoichiometric tuning of organic inputs to the coordination chemistry of the substrate, offering a mechanistic foundation for precision mine reclamation.

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# Mechanisms underlying rhizosphere regulation of soil organic carbon components and stability by leguminous plants in subtropical karst and non-karst forests

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## ABSTRACT

Leguminous plants play a vital role in enhancing forest ecosystem productivity through their biological nitrogen fixation capabilities. However, systematic research on how they regulate soil carbon composition formation and stability via rhizosphere processes under different subtropical geological conditions (particularly in karst and non-karst systems) remains limited. This study aims to elucidate the mechanisms by which leguminous plants influence soil carbon pool dynamics and stability through rhizosphere processes, providing theoretical foundations for evaluating carbon sink functions and ecological management in subtropical forests. The research focused on typical leguminous plants and their non-leguminous symbionts in karst and non-karst forests. Soil carbon components were measured including particulate organic carbon (POC), mineral-bound organic carbon (MAOC), and iron-bound organic carbon (FeOC). Plant-derived carbon (lignin phenols) and microbial-derived carbon (aminosaccharides) were analyzed using biomarker methods. Simultaneously, soil microbial biomass carbon, nitrogen, carbon cycle-related enzyme activities, and physicochemical properties were measured. Statistical methods such as redundancy analysis and path analysis were employed to identify key drivers and pathways influencing soil carbon stability. Results showed that leguminous plants significantly enhanced soil carbon stability, with microbial-derived carbon (measured by aminosaccharides) contributing more to carbon stability than plant-derived carbon (measured by lignin phenols) in rhizosphere soils. Both microbial activity and residue accumulation in leguminous plant rhizosphere soils were significantly higher than in non-leguminous plants, confirming the existence of a microbe-centered carbon stabilization pathway. In subtropical forests, leguminous plants do not primarily contribute to stable carbon pools through litter input. Instead, they significantly enhance mineral-bound organic carbon accumulation and stability by stimulating rhizosphere microbial activity and promoting microbial biomass formation and transformation. While this carbon sequestration pathway exists in both karst and non-karst systems, it is particularly pronounced in calcium-rich, high-pH karst soils. This study reveals key regulatory mechanisms of leguminous plants in forest soil carbon sequestration through rhizosphere microbial processes, providing crucial scientific insights for understanding subtropical forest carbon cycling and advancing plant function-based ecological management strategies.

**Keywords:** leguminous plants, rhizosphere processes, soil carbon stability, microbial carbon, mineral-bound organic carbon, subtropical forests

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# Soil organic carbon formation from plant and microbial residual carbon: Effects of home-ffeld advantage and root litter quality

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**ABSTRACT**

Home-Field Advantage (HFA) hypothesis states that microorganisms specialized in decomposing local litter result in faster in situ decomposition compared to ex situ, enhancing soil organic carbon (SOC) formation in situ soils. Short-term litter decomposition (e.g., < 3 years) typically exhibits the HFA effect. However, it remains unclear whether long-term (e.g., > 5 years) microbial adaptation to substrates in situ or ex situ leads to a loss of HFA and how this impacts SOC accumulation from plant and microbial sources. To address this issue, we conducted a 7-year *in situ* and *ex situ* decomposition experiment using three typical root litters with different quality: Stipa bungeana (C/N = 81.7), Thymus mongolicus (C/N = 56.6), and Artemisia sacrorum (C/N = 43.2). Our ffndings challenge the conventional perspective by showing that HFA declines over time, likely due to long-term microbial adaptation to ex situ soil. This suggests that microorganisms can eventually acclimate to new environments, thereby reducing initial advantages observed in situ. Despite this, a pre-existing strong HFA accelerated root litter decomposition and SOC formation, increasing SOC by 19.9–152.7% under in situ. This acceleration was primarily due to enhanced in situ microbial "in vivo turnover," as evidenced by signiffcant increases in fungal necromass C (294.6–312.1%) and extracellular polymeric substances protein (EPS-protein, 4.8–92.1%). Conversely, plant residual C contributed more to SOC in ex situ (14.3–17.8 %) than in situ (2.5–9.0 %), indicating stronger physical migration of plant residual in ex situ. Low-quality litter facilitated fungal residual C, EPSprotein, and SOC accumulation both in situ and ex situ, suggesting its suitability for biomass synthesis and microbial residual pool formation. This study clariffes the weakening of the HFA over time and the signiffcant contribution of low-quality litter in increasing SOC. This study elucidates the mechanisms by which root decomposition enhances SOC accumulation, highlighting the critical role of HFA in root litter decomposition dynamics.

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# Warming alters fresh-carbon assimilating bacterial community relevant to priming effect in Mollisols

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## ABSTRACT

Soil microbial response to warming may potentially contribute to the positive priming effect, i.e. accelerating the decomposition of native soil organic carbon (SOC) under the outsourced carbon (C) input. Investigating microbiota that metabolize the outsourced C is essential to deciphering the mechanism of priming effect in response to warming and thus mitigating the SOC loss under warming climate. In this work, we monitored the priming effect at 25, 35 and 45°C over four weeks with weekly addition of $^{13}$C-glucose, and subsequently revealed microbial assemblage metabolizing glucose with the DNA stable-isotope probing (DNA-SIP) method. And a meta-analysis further synthesized bacterial community response to different warming conditions. This study generated novel findings that warming initially inhibited the priming effect, and decreased bacterial α-diversity, K/r-strategists ratio (K/r) and recalcitrant C/labile C gene ratio (R/L) in week 1, suggesting that at the onset of the outsourced C input, the increased proportion of r-strategists preferentially utilize the added glucose over SOC to meet their C and energy demands. Yet, in week 4, positive priming effects were intensified by warming with up to 3.8-fold increase at 45°C. Additionally, the primed C was positively correlated with K/r, R/L, and the abundances of chitin degradation genes in week 4. These functions concurred with an increase in the abundance of resource-acquisition strategists such as *Streptomyces* affiliated to Actinobacteria under warming conditions over time. From week 1 to 4, warming induced a distinctive change in glucose-assimilating bacterial community compositions with a particular decrease in the relative abundance of Actinobacteria while an enriched abundance of Chloroflexi. Taken together, warming-triggered change of priming effect depended on alternation of microbiota and metabolic function over time. These findings provide important insights of how warming mediates microbial metabolic use of fresh C and subsequent SOC mineralization, reflecting the positive feedback between soil C emission and climate warming.

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# Microbial Interactions as a Primary Regulator of Soil Organic Carbon Age

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## ABSTRACT

This study aimed to elucidate the spatial distribution patterns of soil organic carbon (SOC) age and soil microbial diversity, and to explore the relationships among microbial diversity, microbial network complexity, and SOC age. In addition, we quantitatively assessed the relative contributions of microbial diversity, network complexity, climate, vegetation, and soil properties to SOC age. Using global measurements of soil radiocarbon ($\Delta^{14}C$) and environmental variables, we developed nine machine-learning models to predict SOC age and identified the optimal predictive model. Based on global soil microbial 16S rRNA gene data combined with environmental variables, microbial network analysis, multiple regression analysis, random forest modeling, and structural equation modeling were applied to examine the relationships between SOC age and soil microorganisms and to identify the primary drivers of SOC age. Soil microbial richness significantly decreased with increasing absolute latitude ($P < 0.001$), showing high richness near the equator and generally lower richness at high latitudes. Among the nine machine-learning models, the rule-based regression model achieved the best predictive performance ($R^2 = 0.77$, RMSE = 0.84). Microbial richness and Shannon diversity indices were significantly negatively correlated with both absolute latitude and SOC age ($P < 0.001$). After classifying global soils into young (44–171 years), middle-aged (172–321 years), and old (322–5,035 years) groups, network density followed the order: young soils (0.400) > middle-aged soils (0.285) > old soils (0.125). Multiple regression, random forest, and structural equation modeling consistently indicated that microbial network complexity explained the largest proportion of variation in SOC age (34%), far exceeding the contributions of vegetation (10%) and climate (6%). Global SOC age is significantly and negatively associated with soil microbial diversity and network complexity. Older SOC is characterized by lower microbial diversity and simpler microbial network structures. Microbial network complexity is a key determinant of SOC age, with a much stronger influence than traditional factors such as vegetation and climate. These findings provide new insights into the mechanisms controlling SOC age and suggest that microbial network properties should be explicitly considered in future simulations of SOC dynamics.

**Result:**

Using publicly available soil microbial diversity datasets, we analyzed their global distribution patterns and spatial variations. The results showed that soil microbial richness decreased significantly with increasing absolute latitude. Microbial richness was relatively high around mid-latitudes (~40°), whereas it was markedly lower at high latitudes (~70°).Furthermore, across nine representative global ecosystems, soil microbial richness followed the order: tropical/subtropical grasslands (4,801) > tropical/subtropical forests (4,213) > temperate forests (4,100) > Mediterranean and montane shrublands (3,830) > croplands (3,580) > temperate grasslands (3,526) > boreal forests (3,461) > deserts (2,960) > tundra (2,469).

Globally, radiometric measurements of soil organic carbon (SOC) were obtained from 4,560 soil samples at depths of 0–3 m, and the corresponding SOC ages were calculated (Figure 1A). A model was constructed using 22 environmental variables with a variance inflation factor (VIF) less than 10, including 11 soil property variables, 2 climate variables, and 9 topographic variables (Figure 1B). Among the nine machine learning models constructed, the CU-based model showed the best predictive performance ($R^2$=0.77, RMSE=0.84), followed by the RF model ($R^2$=0.75, RMSE=0.84), while the MNN-based model showed the worst predictive performance ($R^2$=0.38, RMSE=1.47, Figure 1C). Therefore, the CU model was selected as the optimal model for SOC age prediction analysis, and environmental factors at the same locations as the microbial sampling sites (Figure 1B) were used for SOC age prediction. Of particular note is that the SOC ages predicted by the regular regression model were divided into three groups in ascending order: young soils (44–171 years), middle-aged soils (172–321 years), and old soils (322–5035 years), and these three groups were used for subsequent analysis. Subsequently, the SOC ages corresponding to 484 soil microbial samples worldwide were predicted based on the CU model (Figure 1A). The results show that the age of SOC increases significantly with increasing absolute latitude ($P<0.001$, Figure 1B). In nine typical ecosystems globally (Figure 1C), the SOC ages are as follows: tundra (1281 years) > desert (449 years) > arborescent forest (436 years) > Mediterranean/mountain shrubland (423 years) > farmland (289 years) > temperate grassland (284 years) > tropical/subtropical forest (233 years) > temperate forest (230 years) > tropical/subtropical grassland (131 years).



**Figure 1. Global soil organic carbon age distribution and prediction model construction**

Soil microbial diversity (richness index and Shannon index) showed a significant negative correlation with SOC age ($P<0.001$, Figure 2A). As microbial diversity increased, the age of the SOC decreased. After dividing global soil samples into juvenile, middle-aged, and elderly groups, no significant difference in microbial diversity was found between the juvenile and middle-aged groups, but significant differences were found between the juvenile and elderly groups, and between the middle-aged and elderly groups ($P<0.001$, Figure 2A). Furthermore, network topology parameters (number of edges, average path length, degree centralization, and betweenness centralization) were all significantly correlated with SOC age ($P<0.001$, Figure 2B). Microbial co-occurrence network analysis revealed significant differences in microbial networks among different SOC age groups (Figure 2C). The microbial network structure of the adolescent SOC age group was the most complex, with a network density of 0.400 (Figure 2C); the microbial network structure of the elderly SOC age group was the simplest, with a network density of 0.125 (Figure 2C). The number of nodes, the number of edges, and the average degree of the microbial network structure in the adolescent SOC age group were significantly higher than those in the elderly group, but the modularity of the adolescent group was the lowest (Figure 2C).

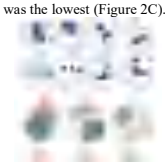


**Figure 2. Relationship between soil microorganisms and SOC age**

Multiple regression models showed that microbial network complexity, vegetation, climate, soil properties, and microbial diversity collectively explained 58% of the variance in SOC age. Among these, microbial network complexity contributed the most to SOC age, followed by vegetation, climate, soil properties, and microbial diversity (Figure 3A). The random forest model yielded similar results, with microbial network complexity, vegetation, climate, soil properties, and microbial diversity explaining 82% of the variability in SOC age. Notably, of the 15 factors in the random forest model, as many as 12 had a significant impact on SOC age (Figure 3B). Among the variables, microbial network complexity had the highest explanatory power. The importance of individual variables was ranked as follows: degree centralization (70%) > NDVI (38%) > number of edges (36%) > average path length (35%) > NPP (33%) > MAT (32%) > MAP (30%) > median centralization (29%) > pH (18%) > SOC (17%) > richness index (16.5%) > Clay+Silt (16%) (Figure 3B). Furthermore, the structural equation model (SEM) explained 54% of the total variance in soil organic carbon age. Negative effect factors included network complexity, vegetation, climate, and microbial diversity, while positive effect factors included soil properties (Figure 3C).



**Figure 3. The explanatory power of the multiple regression model for environmental factors in assessing the global SOC age.**

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# From incubations to landscapes: compensatory thermal adaptation and substrate effects constrain microbial carbon processing in forest soils across China

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## ABSTRACT

Soil microorganisms regulate the turnover of organic carbon (C) and strongly influence terrestrial C–climate feedbacks. However, the magnitude and spatial distribution of compensatory thermal adaptation in key microbial processes—respiration, growth, and carbon use efficiency (CUE)—remain poorly quantified at landscape scales. Moreover, how substrate supply modifies these adaptive responses is still unclear, limiting their representation in process-based and Earth system models. Here, we quantified compensatory thermal adaptation and tested substrate modulation along a forest transect spanning temperate, subtropical, and tropical forests in eastern China, where mean annual temperature (MAT) ranged from –4.4°C to 22.4°C. We incubated topsoil (0–10 cm) at 12°C, 20°C, and 28°C with and without exogenous substrate addition, quantified microbial respiration, growth, and CUE, and used linear mixed-effects and multiple regression models to partition the effects of thermal adaptation and substrate availability. We then combined model coefficients with gridded climate and forest datasets to derive spatially explicit estimates of the magnitude of thermal adaptation (MTA) and the magnitude of substrate effects on thermal adaptation (MSTA) across Chinese forests. Across the transect, microbial respiration and growth (and generally CUE) declined with increasing site MAT when measured at the same incubation temperature, consistent with compensatory thermal adaptation; thermal-adaptation model scenarios provided further support for this pattern. Linear regression analyses further showed that the strength of compensatory thermal adaptation increased along the MAT gradient (stronger for growth than for respiration), and that substrate supply simultaneously amplified this adaptive response for respiration, growth, and CUE. Upscaling to Chinese forests showed that the MTA was negative in ~90% of forest areas, indicating that soil microbial generally exhibit compensatory thermal adaptation, while the MSTA was generally positive across most forests, indicating widespread substrate further amplified the compensatory effects. Together, these findings show that microbial communities in warmer forests are strongly thermally adapted and that substrate supply reinforces this compensatory response, there-by constraining the apparent temperature sensitivity of soil C cycling. Explicitly rep-resenting both microbial thermal adaptation and its resource dependence is essential to avoid overestimating positive soil C–climate feedbacks under future warming.

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# Coupled temperature sensitivity of microbial carbon and nitrogen use efficiencies in forest soils on a continental scale

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## ABSTRACT

Microbial carbon and nitrogen use efficiencies (CUE and NUE) are critical regulators of soil carbon and nitrogen cycling, with their temperature sensitivities playing a pivotal role in mediating biogeochemical feedbacks under global warming. However, the characteristics and relationship of the temperature sensitivity ($Q_{10}$) for both CUE and NUE under varying temperature backgrounds are still poorly understood. Here, we quantified the $Q_{10}$ of CUE and NUE in 55 soil samples collected from a ~4000 km latitudinal forest transect in eastern China. We further identified key drivers that shaped $Q_{10}$ variability from climatic, edaphic, and microbial factors. On average, $Q_{10}$ was 1.22 ± 0.08 for CUE and 1.46 ± 0.13 for NUE. The strong correlation between the $Q_{10}$ of CUE and NUE suggests a coordinated thermal response of microbial carbon and nitrogen metabolism. Notably, both $Q_{10}$ values declined with increasing incubation temperature, indicating that microbial CUE and NUE are more temperature-sensitive at lower temperatures. At lower incubation temperature interval (12-20 °C), edaphic properties and microbial community attributes (especially soil C/N ratio, DOC/DON ratio, and fungal diversity) were dominant predictors, accounting for 96.9% of the variance in the $Q_{10}$ of CUE. For the $Q_{10}$ of NUE, microbial factors and climatic (particularly fungal diversity and precipitation) explained 96.8% of the variance. In contrast, at the higher temperature interval (20-28 °C), climatic and edaphic properties (especially precipitation and soil N:P ratio) became the primary drivers, explaining 90.6% of the variance in the $Q_{10}$ of CUE. Regarding the $Q_{10}$ of NUE under this conditions, microbial and edaphic attributes (especially soil N/P ratio, DOC/DON ratio, and fungal diversity) were dominant, accounting for 77% of the variance. These findings highlight the importance of temperature context in shaping microbial functional responses and offer novel insights for improving predictions of soil carbon-nitrogen turnover under climate warming.

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# Microbially Constructed Carbon–Mineral–Structural Interfaces: Revealing a Novel Perspective on Soil Texture–Mediated Organic Carbon Temperature Sensitivity

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**ABSTRACT**

Soil organic carbon (SOC) decomposition temperature sensitivity is a key determinant of soil carbon–climate feedbacks, yet its controlling mechanisms remain highly uncertain. Increasing evidence indicates that SOC thermal responses are not solely governed by substrate chemical recalcitrance, but emerge from complex interactions between microbial metabolic activity and soil physico-chemical protection mechanisms. Against this background, we propose an integrative theoretical framework in which soil texture shapes microbial habitats, regulates extracellular polymeric substance (EPS) production, influences aggregate formation and turnover, and modulates the interface exposure of mineral-associated organic carbon (MAOC), collectively determining SOC temperature sensitivity.

Specifically, fine-textured soils can enhance microbe–mineral interactions and aggregate stability via EPS-mediated binding, thereby increasing MAOC stability while reducing substrate accessibility and microbial turnover rates. In contrast, coarse-textured soils tend to increase organic carbon exposure, accelerate aggregate turnover, and enhance microbial accessibility to labile substrates, resulting in higher SOC decomposition temperature sensitivity. We further emphasize that MAOC stability is "conditional," being regulated by interface exposure and microbial activity under warming scenarios, rather than being absolutely stable.

In summary, SOC temperature sensitivity arises from multi-scale interactions among soil texture, microbial physiological traits, carbon availability, and physico-chemical protection mechanisms. We also discuss key future research directions, including the quantitative characterization of MAOC exposure–protection states, coupling microbial carbon use efficiency with temperature responses, and incorporating aggregate turnover dynamics into carbon cycling models. This integrative framework provides novel insights into SOC thermal responses and establishes a conceptual basis for improving soil carbon cycle predictions under climate warming.

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Figure 1. Interface-driven temperature sensitivity of soil organic carbon.



Figure 2.Microbial EPS–aggregate interface regulation of SOC temperature sensitivity



Figure 3.Soil texture-driven cascade processes controlling MAOC temperature sensitivity (Q10)

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# Divergent responses of plant lignin phenols and microbial residues to global change: a global meta-analysis

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**ABSTRACT**

Soil organic carbon (C) is primarily derived from plant and microbial residues; however, the global distribution and contribution of different residues inputs to soil C storage under global change remain poorly understood. We conducted a global meta-analysis including 412 observations from 81 studies on microbial residues and 127 observations from 32 studies on plant residues. The results showed that nitrogen (N) addition increased fungal microbial residue C (MRC, +8.40%), bacterial MRC (+5.25%), and total MRC (+7.44%), thereby contributing to enhanced soil organic C (SOC) formation. Warming enhanced total MRC (+6.89%) but reduced plant-derived C, as indicated by significant declines in vanillyl phenols (−24.60%) and cinnamyl phenols (−16.75%), which was associated with decreased SOC. Decreased precipitation reduced total MRC (−10.54%), whereas increased precipitation significantly enhanced lignin phenols (+54.08%) while reducing total MRC (−11.41%). However, changes in precipitation had no significant effect on SOC content. We found that under N addition, MRC responded more strongly in topsoil than in subsoil, whereas warming exerted stronger effects on both plant- and microbial-derived residues in subsoil layers. This study advances our understanding of how plant and microbial residues respond to global change and highlights the need for greater attention to long-term experiments and subsoil responses to global change in future research.

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# Symbiosis in an asymmetrical day-night high-$CO_2$ world: Interactive effects of arbuscular mycorrhizal fungi and elevated $CO_2$ on legume nutrition and soil fertility

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## ABSTRACT

**Background and Objectives**: The interactive effects of arbuscular mycorrhizal fungi (AMF), elevated atmospheric $CO_2$ ($eCO_2$), and their combination on legume nutrient dynamics and soil fertility remain poorly understood. This knowledge gap extends to the relationship between glomalin-related soil protein (GRSP) and key soil parameters such as organic carbon (C), total nitrogen (N), and enzyme activity.

**Methods**: To address this, we investigated the growth, tissue nitrogen (N), phosphorus (P), and potassium (K) concentrations, and nutrient use efficiency (NUE) of nodulated fababean (*Vicia faba*) inoculated with *Rhizobium leguminosarum* bv. NM353. Plants were grown for 12 weeks under asymmetric ambient $CO_2$ (410/460 ppm day/night) or $eCO_2$ (550/610 ppm day/night), with or without inoculation by the AM fungus *Funneliformis mosseae*.

**Results**: Our results showed that $eCO_2$ significantly enhanced AMF root colonization and nodule biomass. While $eCO_2$ reduced shoot N, P, and K concentrations, it increased total tissue accumulation of these nutrients and their use efficiency, driven by greater biomass production. $eCO_2$ also promoted belowground C allocation but did not alter soil available N, P, or K. In contrast, AMF symbiosis increased the accumulation of C, N, P, and K in both plant and soil pools, effectively enhancing plant nutrient uptake under $eCO_2$. Notably, plant acquisition of soil $NO_3^-$–N and $NH_4^+$–N responded differentially to AMF and $eCO_2$ treatments. We further found that daytime, nighttime, and combined day/night $eCO_2$ levels increased AMF colonization, soil organic C (SOC), total N, and all GRSP fractions in mycorrhizal soils. Daytime $eCO_2$ reduced soil TN in non-mycorrhizal soils, a limitation mitigated by AMF presence. Nighttime and combined $eCO_2$ treatments significantly elevated β-glucosidase and protease activities in both soil types, with effects more pronounced in AMF soils. GRSP concentrations were positively correlated with mycorrhization, SOC, total N, and β-glucosidase activity.

**Conclusions**: In conclusion, the interaction between AMF symbiosis and $eCO_2$ enhances plant C accumulation and soil nutrient uptake, indicating a critical role for mycorrhizal management in legume cultivation under future atmospheric conditions. Our findings underscore that, beyond mycorrhization, the distinct and combined effects of diurnally varying $eCO_2$ significantly influence soil C and N cycling. Future research should employ multi-species AMF and microbial consortia under field conditions to explore these interactions amidst concurrent global change stressors such as warming and drought.

**Keywords:** Fababean, glomalin-related soil protein, mycorrhization, $N_2$-fixation, soil organic carbon

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# Global warming decreased soil organic carbon stock via increasing organic matter lability and heterotrophic respiration

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**ABSTRACT**

Global warming can simultaneously increase plant net primary production (NPP) as a carbon (C) input and microbial decomposition of organic matter as a C output, making it challenging to predict its overall impact on soil organic C (SOC) accumulation. To evaluate the effects of global warming on SOC dynamics in paddy soils, current and projected climate conditions were simulated using Open Top Chambers. In the future climate scenario, atmospheric temperature and $CO_2$ concentration were elevated by 2 °C and 200 ppmV, respectively. Chemical or organic fertilizer treatments were added in both climate conditions. In the organic fertilizer plots, cover crops were cultivated during the cold fallow season and fully incorporated as green manure before rice transplanting. Changes in SOC stock during the cropping period were assessed using a net ecosystem C budget analysis, representing the balance between C inputs and outputs. Global warming reduced rice NPP by 9–20% under the same fertilization, while increasing microbial decomposition of organic matter by 28–98%. It also substantially increased dissolved organic matter in the soil without discriminating against chemical composition, further enhancing microbial decomposition. Consequently, SOC accumulation was markedly decreased under future climate conditions. While the cultivation and incorporation of cover crops increased SOC under current climate conditions, this practice was insufficient to enhance SOC accumulation under projected future climates. Overall, under future climate conditions, larger amounts of organic amendments may be required to achieve meaningful increases in SOC storage.

**Keywords:** net ecosystem carbon budget, net primary production, soil respiration, climate change

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# Decades of no-till coupled with warming improves topsoil soil organic matter accrual via stimulate microbial carbon use efficiency

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**ABSTRACT**

Conservation tillage such as no-till has been recommend as a potential strategy to sequester soil organic matter (SOM) and mitigate climate change, but how this alternative farming altered SOM biochemistry remains elusive, particularly under simulated warming condition. Here, we uncovered the SOM composition and origins, and underlying microbial-mediated processes from a conservation tillage trial under warming in North China. Soil samples (i.e., 0-5, 5-15, and 15-30 cm) were collected from four treatments: moldboard plow (MP), moldboard plow with warming (MPw), no-till (NT), and no-till with warming (NTw). Considering tillage effects, NTw (*cf.* MPw) increased both bacterial and fungal biomass in topsoil. Further, NT (*cf.* MP) decreased oligotrophic K-strategists, including Chloroflexi and Gemmatimonadetes. Regardless of warming, no tillage enhanced the relative abundance of recalcitrant dissolved organic matter (DOM), but decreased biodegradable DOM compounds such as carbohydrates, proteins in topsoil. Both biomarker (higher total lignin phenols) and $^{13}$C-nuclear magnetic resonance (higher aromatic and phenolic group) collectively revealed the enhanced preservation of lignin phenols in NTw (*cf.* MPw). No tillage (NT and NTw) significantly increased glomalin-related soil protein (GRSP) in the surface soil, while warming have no effects on those molecules. Moreover, NT enhanced bacterial and fungal necromass relative to MP in the topsoil. Considering warming effects, warming decreased catabolic enzymes activities ($\beta$-1,4-glucosidase and leucine aminopeptidase) under two tillage systems, while exerted the strong positive influence on microbial carbon use efficiency. Collectively, NTw (*cf.* MPw) may have the potential to enhance the process of bacterial anabolism and *in vivo* turnover (reflecting by microbial necromass and GRSP), thus improve microbial carbon pump efficiency and OM formation in a future warmer world. Moreover, no-till treatments (NT, NTw) increased the fraction of refractory DOM (i.e., condensed aromatic structures and tannin) relative to conventional farming. Our work provides insights into the potential benefits of conservation agriculture for long-term carbon sequestration because no tillage improves resilience to the effects of climate warming.

# Context-dependent dominance of plant detritus or microbial necromass in soil organic carbon accrual

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**ABSTRACT**

Soil organic carbon (SOC) originates from both microbial and plant sources, yet the scarcity of large-scale paired comparisons between these two carbon sources has left their relative importance a topic of intense debate—spawning conflicting paradigms of SOC formation. Compounding this uncertainty, how shifts in their relative contributions mediate SOC accrual—an essential link for understanding carbon sequestration mechanisms—also remains poorly resolved. To address these unresolved questions, we compiled a comprehensive continental-scale paired dataset of soil amino sugars (microbial-derived) and lignin phenols (plant-derived)—two widely accepted biomarkers for quantifying SOC sources. Using this dataset, we estimated the contents of microbial necromass carbon (MNC) and plant detritus carbon (PDC), and quantified their relative importance via the MNC-to-PDC ratio and its associational pattern with SOC content. Our analysis revealed order-of-magnitude variations in the MNC-to-PDC ratio, both within and across ecosystem types and soil depths. Notably, MNC dominated SOC pools in 68%–70% of grassland soils and 67%–85% of forest soils, whereas PDC prevailed in over 59% of cropland soils and 83% of wetland soils. MNC contributions to SOC increased with soil depth. Moderation analysis identified three distinct scenarios describing the relationship between SOC content and the MNC-to-PDC ratio. Building on these findings, we developed a context-explicit conceptual framework to resolve recent debates regarding how carbon sources influence SOC formation. In this framework, the dominant SOC formation pathway and the relative decomposability of carbon sources—regulated by mean residence time and mineral protection potential, respectively—mediate the SOC and its sources link. Collectively, our results underscore SOC's multi-source nature, challenging the prevailing microbe-centric paradigm that emphasizes the microbial-derived SOC predominance and advocating for a holistic, integrated perspective on SOC genesis that accounts for diverse environmental contexts. Future SOC management strategies should consider the context-specific relevance of SOC sources and formation pathways.

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# Thermal acclimation of soil microbial respiration across permafrost ecosystems: contrasting roles of autotrophic and heterotrophic microorganisms

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**ABSTRACT**

Many studies have shown that soil microbial respiration can exhibit thermal acclimation, which suppresses the increase in respiration rates under warming and thereby mitigates the positive feedback between terrestrial carbon cycling and climate warming. Based on this background, we selected soils from four permafrost-region ecosystems in China that represent a gradient in the relative dominance of autotrophic versus heterotrophic microorganisms, and conducted a simulated warming incubation experiment to investigate patterns of thermal acclimation in soil microbial respiration.

Our results showed that in the forest, respiration rates in warming soils were significantly lower than those in control soils, indicating a compensatory response of microbial respiration. Moreover, the effect size of warming on microbial respiration decreased from forest to desert to meadow. In contrast, the swamp meadow exhibited an enhancement response of microbial respiration.To further explore the mechanisms underlying differences in thermal acclimation among permafrost-region ecosystems, we found that both the heterotroph-dominated forest and the autotroph-dominated desert ecosystem exhibited compensatory responses. In forest, warming exerted the strongest negative effects on heterotrophic metabolic indicators, leading to a pronounced compensatory response. In the desert ecosystem, although heterotrophic metabolic indicators did not change significantly, a compensatory response was still observed, likely because the relatively high proportion of autotrophic microorganisms partially offset heterotrophic $CO_2$ release through autotrophic carbon fixation. However, this mechanism requires further verification. In contrast, two ecosystems dominated by autotrophic microorganisms-the swamp meadow and the meadow-exhibited opposite response patterns, with the swamp meadow showing an enhancement response. In the swamp meadow, excessive soil water content resulted in prolonged anaerobic conditions, under which the compensatory effect of autotrophic carbon fixation on warming-induced increases in respiration was weakened or even lost. Meanwhile, warming stimulated heterotrophic microorganisms to upregulate their metabolism, increasing carbon-degrading enzyme activities and accelerating organic carbon decomposition, ultimately leading to increased microbial respiration and an enhancement response. The meadow had lower soil moisture and more adequate oxygen availability, allowing autotrophic microorganisms to effectively fix the released $CO_2$ and resulting in a compensatory response of microbial respiration. Thus, although both meadow ecosystems were dominated by autotrophic microorganisms, differences in soil moisture conditions led to contrasting response patterns.

In summary, this study provides initial evidence for differential roles of autotrophic and heterotrophic microorganisms in regulating thermal acclimation of soil microbial respiration across permafrost-region ecosystems.

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# Effects of warming on soil organic carbon

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**ABSTRACT**

Based on meta-analysis, we demonstrated that warming reduces soil organic carbon (SOC) content. The primary mechanisms identified are as follows: 1) Warming can decrease microbial carbon use efficiency by reducing microbial diversity, thereby lowering SOC content [1]; 2) Warming can reduce microbial biomass by decreasing soil moisture, which subsequently leads to a decline in SOC [2]; 3) A significant reduction in SOC occurs only when the warming magnitude exceeds 2°C, lasts more than 2 years, and affects surface soil layers [3]; 4) Warming amplifies the response of SOC to other environmental factors: it exacerbates carbon loss induced by drought and enhances the carbon gain stimulated by elevated $CO_2$ and nitrogen fertilization [4].

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# Recognizing the role of soil microorganisms in organic carbon accumulation in drylands

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**ABSTRACT**

Global warming is causing the expansion of drylands, which presents significant challenges in understanding the processes of soil organic carbon (SOC) accumulation. Soil microorganisms play an important role in the turnover and stabilization of organic carbon, but their role in dryland ecosystems remains poorly understood. By analyzing soil molecular biomarkers and microbial data from typical dryland ecosystems across a continental-scale aridity gradient in northwestern China, this study explores the role of soil microorganisms in organic carbon accumulation under increasing aridity. The results show that as aridity intensifies, microbial-derived carbon gradually decreases, primarily due to water limitations that suppress microbial community activity and growth. In contrast, plant-derived carbon gradually increases with increasing aridity, as water limitation not only suppresses microbial community activity but also restricts microbial decomposition functions, leading to a reduced ability of microorganisms to decompose plant-derived carbon. These findings challenge the traditional view that microbial-derived carbon dominates SOC accumulation, a perspective that does not hold in dryland ecosystems. It also suggests that, with the continued expansion of drylands in the future, soil organic carbon will primarily be derived from plant sources.

**Keywords:** Drylands;Soil organic carbon; Microbial-derived carbon; Plant-derived carbon; Microorganisms

# Reconstruction of Rhizosphere Soil Microenvironments: Synergistic Plant-Microbe Purification Mechanisms and Practices

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**ABSTRACT**

Excessive nitrogen is a key factor triggering wetland eutrophication and functional degradation. Enhancing nitrogen removal performance via regulation of biological components within wetland ecosystems has become a research focus in wetland science. This report elaborates on the synergistic nitrogen removal mechanisms of wetland plants and microorganisms under complex environmental conditions, including root oxygen release, root exudate-mediated carbon supply, and nitrification-denitrification coupling. It addresses the bottleneck of limited nitrogen removal efficiency under low-temperature and high-salinity stress, and proposes novel techniques and practical applications for synergistic nitrogen removal by wetland plant-microbe consortia.

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# Soil Microbial Diversity and Carbon Stability for Climate Resilient Land Management in the Western Ghats

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**ABSTRACT**

Land use change (LUC) alters the soil carbon dynamics and microbial functioning, which in turn influence the ecosystem resilience and climate regulation. The Nilgiri Hill Region (NHR) a UNESCO World Heritage site and global biodiversity hotspot has undergone widespread transformation from native forests to plantations and croplands. Our study evaluated the impact of LUC on soil and microbial profile across six major ecosystems (evergreen forest, deciduous forest, scrubland, forest plantation, tea plantation, and cropland) of NHR. Soil samples from all these ecosystems were analyzed for physical, chemical, and biological properties including metagenomic characterization and carbon pool fractionation. Results revealed that forest ecosystem maintained higher total organic carbon, recalcitrant carbon pools, microbial biomass, and enzyme activities compared with converted lands. In comparasion the tea and cropland exhibited reduced carbon stability, lower microbial efficiency and elevated $CO_2$. Random Forest modeling effectively predicted the carbon distribution, identifying key predictors such as bulk density, aggregate stability, and aggregate associated carbon. Carbon Management Index and Soil Quality Index revealed substantial deterioration of soil health under converted land uses. Metagenomic profiles emphasized a decline in microbial diversity and functional genes associated with carbon sequestration in disturbed ecosystems. These findings highlights that LUC in the NHR decreases recalcitrant carbon concentration and microbial carbon use efficiency, leading to enhanced carbon emissions and degraded soil health. Thus, integrating metagenomic insights with predictive modeling provides a solid framework for understanding soil carbon microbe interaction and developing sustainable land management strategies for climate resilient ecosystem.

**Keywords:** Soil Carbon Dynamics, Soil Carbon Microbe Interaction, Predictive Modeling, Soil Ecology

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# Differences of Soil Carbon Sequestration Efficiency of Typical Cropland in China, UK and USA

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**ABSTRACT**

It is generally known that soil organic carbon (SOC) stocks tend to increase with increasing C input, whereas the C sequestration efficiency (CSE), i.e. the conversion ratio of C input to SOC, differs depending on the amount and type of C input. A better understanding of the CSE characteristics is urgently needed to effectively sequester C in agroecosystem, thereby improving soil fertility and mitigating climate change. We studied data from 12 typical long-term dryland experiments, which varied in experimental duration, to clarify the responses of soil CSE to different fertilizations, including no fertilizer, chemical nitrogen, phosphorus and potassium, chemical fertilizers plus manure and straw, and manure only. Variance partitioning analysis (VPA) and extreme gradient boosted tree (XGBoost) regression modelling were used to comprehensively assess the key drivers of CSE in the plough layer. The eight long-term experiments in China indicated that the CSE has remained relatively constant over nearly four decades of fertilization, with SOC linearly increasing with C input. VPA illustrated that the CSE of the main dryland region of China was mostly controlled by edaphic characteristics, especially the soil C/nitrogen (N) ratio and clay content, followed by C input and climate. Manure amendment had the most significant fertilization effect on SOC sequestration with an average CSE of 14.9%, followed by chemical fertilization (9.0%) and straw return treatment (7.9%). Based on the four classical long-term experiments with SOC showing nonlinear changes over time, the negative exponential dynamics of soil CSE was fully captured by the model ($CSE=b+a*e^{-k*Cinput}$, $P < 0.01$). The CSE in the Chromic Luvisol of southeast England experienced a rapid decrease before C input reached 123-315 t C $ha^{-1}$, and a similar trend was observed in the Mollisols of the Central Great Plains of America before C input levels of 93-145 t C $ha^{-1}$. Subsequently, the CSE continued to decrease more slowly towards an asymptotic value. A larger asymptotic CSE value was observed in the manure applied treatments (2.45-10.25%) than in the chemical fertilizer treatments (0.48-3.85%). XGBoost regression modelling identified C input, MAT and total N stock as critical factors for soil CSE over a century of fertilization. Soil CSE tends to remain constant as SOC increases linearly with C input. However, when SOC exhibits non-linear changes, CSE is exponentially decreased and eventually approaches an asymptote. Additionally, our results suggest that manure amendment is a sustainable practice for improving CSE in dryland cropping systems. This study provides empirical evidence and insights into the optimal fertilizer strategy for enhancing CSE under long-term fertilization.

**Keywords:** soil organic carbon sequestration, long-term experiment, carbon sequestration efficiency, manure application

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# To reduce $CH_4$ and $N_2O$ emissions whilst maintaining crop yield in rice-wheat system in China with climate change using SPACSYS model

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## ABSTRACT

Context: Climate change is projected to threaten food security and stimulate greenhouse gas emissions. Hence, adaptation measures without sacrificing food production are required.

Objective: To assess possible consequences of rice-wheat system under climate change and to propose possible practices for mitigation.

Methods: The Soil-Plant-Atmosphere Continuum SYStem (SPACSYS) model was tested using datasets from long-term experiment (1991-2019) assessing the impact of different fertilisation on crop production, crop nitrogen (N) content, soil organic carbon (SOC) stock, methane ($CH_4$) and nitrous oxide ($N_2O$) emissions in a Cambisol under rice-wheat system. The validated SPACSYS was then used to investigate the possible mitigation strategies from 2024 to 2100 under climate change scenarios (SSP1-2.6 and SSP5-8.5) and the baseline scenario and mitigation management scenarios, i.e., (i) reduced N application rate by 20 % (RNA), (ii) the introduction of mid-season drainage (MSD) and (iii) integrated management combining RNA with MSD (IM).

Results and conclusions: Results showed that SPACSYS performed effectively in simulating yield and N content in grain and straw, SOC stock and $CH_4$ and $N_2O$ emissions. Scenarios analysis elucidated that RNA would not decrease grain yields for either rice or wheat under the two climate change scenarios. Compared to the baseline scenario, low level of climate change scenario considering the $CO_2$ fertilisation effects (SSP1-2.6_$CO_2$) may benefit wheat yield (28 %) and had no effects on rice yield. In contrast, under the SSP5-8.5 scenario, whether $CO_2$ fertilisation effects are considered or not, both rice and wheat yield could face great loss (i.e., 11.8-29.9 % for rice, 8.3-19.4 % for wheat). The winter wheat would not be suitable for planting in the distant future (2070-2100) due to the incomplete vernalisation caused by warming. The switching from winter wheat to spring wheat from 2070 onward could avoid the yield loss by 8.3-19.4 %. Climate change could decrease SOC sequestration rate. Under future climate change scenarios, IM could significantly decrease $CH_4$ emissions by 56 % and $N_2O$ emissions by 24 %, as such reducing the net global warming potential by 69 % compared to no adaptation. Our simulations suggest that under climate change, crop switching in rice-wheat system combining integrated mitigation practices is possible to mitigate global warming and maintain crop production.

Significance: Our results underscore the significance of integrated adaptation of agricultural systems to climate change.

**Keywords:** Climate change; Crop yield; SOC; GHG; Mitigation; SPACSY

# Does elevated atmosphere $CO_2$ facilitate soil carbon sequestration?

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**ABSTRACT**

Elevated atmosphere $CO_2$ has been shown to increase plant biomass production and exacerbate nitrogen deficiency. However, it is poorly understood how elevated $CO_2$ impacts the dynamics of soil organic matter (SOM). This ABSTRACT provides an overview of our short- and long-term experiments to elucidate this in farming soils. Our meta-analysis shows that elevated $CO_2$ enhances overall soil carbon decomposition and rhizosphere priming, but these increases depend on soil nitrogen supply and crop species. In short-term experiments, elevated $CO_2$ increases rhizosphere priming effect which is positively associated with the amounts of root exudates, the activity of SOM-decomposing enzymes and the labile C-to-mineral N ratio in the rhizosphere. The addition of nitrogen generally decreases rhizosphere priming, depending on nitrogen form, crop species and growth stage, but its direct effect on SOM decomposition differs substantially with soil type. Irrespective of crop species, growth stages and nitrogen forms, the rhizosphere priming effect is positively correlated with rhizosphere pH. The long-term $CO_2$ enrichment tends to decrease total SOM in the topsoil but not in the subsurface soils. It also appears to destabilize SOM in sandy soils. Elevated $CO_2$ does not alter the entire community composition of bacteria and fungi in the rhizosphere or bulk soils but enriches some microbial taxa that may accelerate decomposition of recalcitrant SOM. It is concluded that elevated atmospheric $CO_2$ does not favor SOM sequestration, and that the effects of nitrogen supply on SOM decomposition are complex and deserve further investigation.

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# Soil Carbon Change under Land Use and Climate Change

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## ABSTRACT

Soil carbon stocks are affected by a range of global drivers with two of the main drivers being land use and land management change and climate change (Smith, 2008; Smith, 2012; e.g. Figure 1).

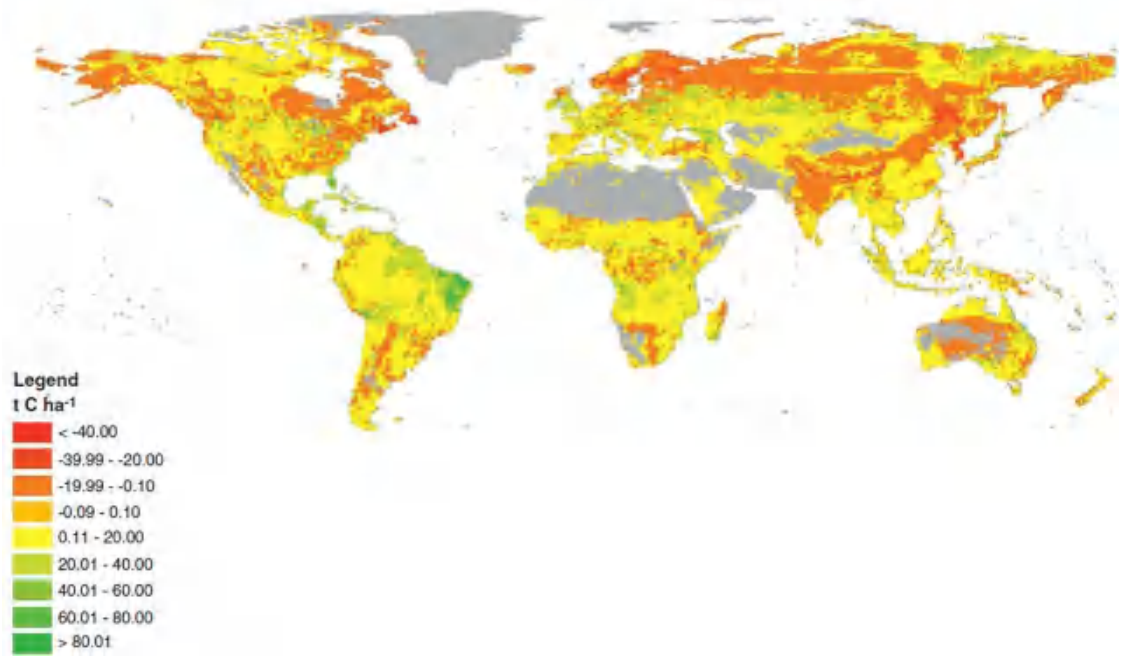



**Figure 1.** Average trend in SOC stock change 1971–2100 across 10 climate scenarios (after Gottschalk et al., 2012).

In this presentation I will draw on 30 years of research into these topics to highlight what we know about the response of soil carbon stocks to land use, land management and climate change, what we still do not know, and what we can do to protect soil carbon stocks form further decline under future climate and land use / land management change (Smith et al., 2024). I include studies representing a range of methodologies, including modelling, measurements, field and laboratory experiments and other forms of evidence.

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# Spatial variation and agronomic impacts of inherent soil productivity on wheat in China

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**ABSTRACT**

Improving soil fertility is essential for securing future food production. Inherent soil productivity (ISP), which reflects the integrated fertility of the soil, is commonly defined as crop yield under unfertilized conditions. However, due to the high diversity of soil and climate conditions in China, the spatial patterns, limiting factors, and agronomic implications of ISP at large scales remain poorly quantified. In this study, we compiled large-scale field data from 12,737 experiments conducted across China's wheat-growing regions to quantify regional variations in ISP and to evaluate the impacts of ISP improvement on agricultural production. We then developed a random forest model integrating soil, climatic, and management practices to identify the key limiting factors of ISP at the county scale and to assess its improvement potential. The average ISP of wheat fields in China is 3.73 Mg ha$^{-1}$, contributing (ISPC) on average 61% to fertilized yield. ISP exhibits significant regional differences, following the order: North China Plain-irrigated > North China Plain-rainfed > Northwest-irrigated > Northwest-rainfed > Northeast > Yangtze River Plain > Southwest. Each unit increase in ISP is associated with an 8% (6–12%) increase in ISPC, resulting in significant improvements in wheat yield and nitrogen use efficiency (NUE), as well as a significant reduction in nitrogen (N) surplus. A random forest model incorporating soil, climate, and management data explained 74% of the variation in ISP, demonstrating high stability and predictive capability. Future improvements in AP by 12.8 mg kg$^{-1}$, AN by 38.8 mg kg$^{-1}$, TN by 0.38 g kg$^{-1}$, pH by 0.46, SOM by 8.91 g kg$^{-1}$, and AK by 52.1 mg kg$^{-1}$, could increase ISP by 0.35 Mg ha$^{-1}$ and ISPC by 3%. Under these conditions, fertilized wheat yield, NUE, and N surplus would reach 6.46 Mg ha$^{-1}$, 62%, and 87 kg ha$^{-1}$, respectively. These findings highlight the crucial role of ISP in enhancing wheat productivity and NUE, and provide a promising strategy to improve soil fertility that supports national food security while mitigating environmental impacts.

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# Integration of artificial intelligence and remote sensing reflectance spectra for regional SOC Mapping

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**ABSTRACT**

Soil organic carbon (SOC) is a major terrestrial carbon reservoir and a cornerstone of soil fertility, directly influencing climate change and human well-being. However, it remains unclear how different spectral data sources and artificial intelligence (AI) modeling strategies jointly shape SOC prediction performance, especially across large and heterogeneous agricultural landscapes. This study systematically evaluated the integration of model-data strategies for SOC prediction on the farmland of the Loess Plateau, a region characterized by fragmented croplands and limited carbon stock data. The results show that the hyperspectral-driven model (CARS-SVM) achieved the highest accuracy, but their reliance on regional-scale hyperspectral datasets restricts practical applications. By contrast, the multispectral-environmental integrations model (SPA-BPNN) delivered robust and scalable performance, offering a feasible pathway for regional SOC mapping. This study establishes a transferable methodological framework for optimizing data–model combinations in heterogeneous agricultural landscapes, thereby supporting carbon management in agroecosystems worldwide.

**Keywords:** Cropland; Environmental factors; Hyperspectral data; MODIS; Multispectral data; SOC

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# Decadal extreme drought reduces alpine subsoil carbon stocks

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**ABSTRACT**

Grassland soil organic carbon (SOC) stocks are increasingly vulnerable to intensified drought. Yet, how long-term, especially extreme, drought affects these C reserves across soil profiles remains unresolved. Here, we present the response of SOC stocks at various depths (0–60 cm) using an experiment involving a 10-year drought gradient (P, 1/2 P, 1/4 P, and 1/12 P, where P is ambient precipitation) in an alpine grassland. We find that extreme drought (1/12 P) caused significant SOC losses in the subsoil, whereas mild to moderate droughts had no significant effects on SOC at any depth. Under extreme drought, SOC stocks declined by 27% in the 20–30 cm layer and 37% in the 30–40 cm layer, while no significant changes were observed in the topsoil (0–20 cm) and the deeper layer (40–60 cm). Subsoil C losses were primarily driven by reductions in mineral-associated organic C (MAOC) rather than particulate organic C (POC). Multi-year extreme drought disrupted soil-microbe-mineral interactions, as indicated by reductions in soil nitrogen availability, microbial biomass, carbon use efficiency, and mineral-binding agents. These changes collectively undermined the formation and stabilization of MAOC. Our findings suggest that prolonged extreme drought can weaken subsoil C storage and stability, highlighting the need to incorporate subsoil processes into Earth System Models to better predict soil C–climate feedback under future drought scenarios.

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# Crop diversification as a climate-smart strategy: A model-based assessment in Mediterranean orchards for soil carbon sequestration and greenhouse gas emissions mitigation

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## ABSTRACT

Soil organic carbon (SOC) sequestration through sustainable soil management practices (SMPs) is a globally prioritised strategy for climate change (CC) mitigation, improving soil fertility, and enhancing agroecosystem resilience. Despite practices like crop diversification and minimal soil disturbance are known to promote carbon retention and reduce greenhouse gas (GHG) emissions, the net long-term climate benefit - especially in CC-vulnerable perennial systems - remains unclear. Hence, this study, for the first time, assesses the long-term effects of diversified versus monocropping systems on SOC stocks, GHG emissions, and the net $CO_2$-equivalent balance in two Mediterranean orchard case studies: a rainfed almond (CS1) intercropped with *Capparis spinosa* and *Thymus hyemalis* and an irrigated mandarin (CS2) intercropped with various cover crops. Using the process-based ECOSSE model, we simulated how crop diversification and SMPs influence SOC dynamics, under both current and projected future climate scenarios (2040-2069 and 2070-2099 periods). Future climate scenarios project higher temperatures, lower precipitation, and increased evapotranspiration, which indicate greater aridity and subsequent hydrological stress. Modelling results showed that crop diversification significantly enhanced SOC stocks in both case studies. In the CS1, diversification increased SOC stock by up to 85 %, with only minor increases in $CO_2$ emissions and negligible impact on $N_2O$ or $CH_4$ emissions. On the other hand, the CS2 showed a greater increase, with SOC stock rising by up to 114 %, with minor $CO_2$ increases and a notable decrease in $N_2O$ and $CH_4$ emissions. This research demonstrates that crop diversification in Mediterranean orchards substantially enhances SOC stocks and provides a robust strategy for long-term climate mitigation, even under challenging future climate projections.

**Acknowledgments**

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# Mechanisms of low carbon sequestration efficiency in the croplands of the eastern Loess Plateau

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**ABSTRACT**

Soil organic carbon (SOC) is a key indicator of soil health and agricultural sustainability. Yet, SOC remains low in the Loess Plateau, and carbon sequestration efficiency (CSE) has not been systematically quantified across cropland systems spanning dominant climate zones. Here, we analyzed the spatiotemporal variability of carbon input and CSE in croplands from 1983 to 2023 across typical agroecological regions in the eastern Loess Plateau. Using geostatistical methods, Random Forest, and path analysis, we identified key drivers of SOC accumulation and CSE under varying climates and soil amendment regimes. Our results reveal a clear north-south gradient in SOC stocks, with higher values in the southern region. Overall, carbon input exhibits an increase from north to south, whereas CSE declines from north to south over the period 1983-2023. Elevation, temperature, initial SOC, and manure-derived carbon were dominant drivers of spatial divergence. The overall low CSE across the Plateau may be attributable to carbon loss driven by persistent soil erosion. The relatively low CSE in the south may result from saturation effects, as higher baseline SOC and sustained carbon inputs limit incremental sequestration. These findings offer region-specific insights to support soil fertility improvement and sustainable agriculture, underscoring the need for erosion-sensitive, carbon-informed land management approaches to enhance soil health and resilience in the croplands of the eastern Loess Plateau.

**Keywords:** Soil organic carbon; Carbon sequestration efficiency; Spatial variation; Cropland; Eastern Loess Plateau

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# Photocatalytic generation of reactive oxygen species from dissolved black carbon: Identification of photoproduction sites

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**ABSTRACT**

As an essential source of the natural soil organic matter, dissolved black carbon (DBC) from biochar can generate reactive oxygen species (ROS), playing significant roles in contaminants degradation and chemical stresses to microorganisms. However, little is known regarding the photoproduction sites to ROS generation, mainly because of its extremely complicated composition. Herein, the ROS generation and photoexcited alteration of DBC were investigated. To investigate the mechanisms of ROS generation, it is essential to identify the determining structures of DBC for ROS generation.

The generation mechanisms of hydroxyl radical (•OH), superoxide anion ($O_2^{\bullet-}$) and singlet oxygen ($^1O_2$) were inferred by employing various model chemicals. Results revealed the vital role of OFGs within DBC in the generation of •OH, $O_2^{\bullet-}$, and $^1O_2$. The photo-excited aliphatic carbonyls greatly contributed to $^{\bullet}OH$, $O_2^{\bullet-}$, and $^1O_2$ generation. Ether groups were identified as the main structural source of $H_2O_2$-dependent $^{\bullet}OH$ generation. The novel non-electron transfer process involved carbonyl, ether, alcohol, and ester groups to produce $O_2^{\bullet-}$ was proposed. The generation of $^1O_2$ depended on the aromatic structures within DBC, while simultaneously dominated by molecular configuration, substituent and weight of aromatic groups. Moreover, we demonstrated the nonnegligible •OH generation from aliphatic carbonyls of DBC, the excited-state carbonyl structures could ABSTRACT H proton and result in homolytic cleavage of $H_2O$. Compared to quinonoid groups, the abundant carbonyls within DBC could be the main structures contributing to ROS generation. The stimulation of aliphatic carbonyls within DBC to the generation of ROS deserved more attention. These findings reveal the vital role of oxygenated functional groups within DBC in the photoactive generation of ROS. The new insights revealed in this study may also provide new angles for interpreting the geochemical cycles of DBC, and thus provides new theoretical information for DBC's environmental geochemical behavior.

**Acknowledgments**

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# Long-Term Organic Fertilization Enhances Particulate Organic Matter Accumulation through Macroaggregate Formation in the Loess Plateau

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## ABSTRACT

Organic amendments are widely recommended to enhance soil organic carbon (SOC) in low-fertility soils. Yet, SOC levels remain persistently low in erosion-prone croplands of the Loess Plateau. Here, we investigate how long-term organic fertilization influences soil aggregation and SOC dynamics in loess soils, based on a 33-year maize field experiment with five treatments: no fertilizer, mineral nitrogen-phosphorus (NP) fertilizer, and NP fertilizers combined with three increasing rates of manure (M1–M3). Results showed that higher manure rates (M2 and M3) significantly increased the proportions of macroaggregates (>0.25 mm) and free microaggregates (0.053–0.25 mm) at the expense of the free silt-clay fraction (<0.053 mm) compared to M0. Concurrently, these treatments substantially enriched SOC content in macroaggregates (40%–81%) and free microaggregates (33%–41%), driving a preferential accumulation of particulate organic matter (POM-C increased by 54%–61%) over mineral-associated organic matter (MAOM-C increased by 18%–24%). Consequently, the apparent carbon conversion efficiency (CCE) of exogenous organic inputs was 6.6% in bulk soil, followed by 5.3% in POM, 5.0% in macroaggregates, and 2.4% in free microaggregates. These results indicate that organic inputs drove the redistribution of carbon into larger aggregates, where fresh organic residues reinforced macroaggregate occlusion, protecting POM from decomposition. In contrast, MAOM stabilization was constrained by mineral surface saturation, as limited reactive surfaces restricted further carbon association, resulting in diminished conversion efficiency under high inputs. These findings suggest that promoting macroaggregate formation and POM enrichment is the key practical strategy for maximizing SOC persistence in dryland loess croplands.

**Keywords:** Soil aggregates; Organic carbon; Long-term organic fertilization; Carbon conversion efficiency; Loess Plateau.

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# Organic amendments differentially regulate POC and MAOC dynamics in topsoil and subsoil

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## ABSTRACT

Organic amendments (including straw, biochar, and organic fertilizers) are widely adopted to enhance soil fertility and organic carbon (SOC) sequestration in agricultural systems. SOC stability is governed by the balance between particulate organic carbon (POC) and mineral-associated organic carbon (MAOC), yet most empirical evidence is derived from surface soils (0-20 cm), leaving subsoil processes (≥20 cm) poorly constrained. We conducted a comprehensive meta-analysis of 108 peer-reviewed studies published between 1990 and 2025, by synthesizing 651 paired observations to quantify the effects of organic amendments on SOC, POC, and MAOC across soil depths. Results indicate that the effects of amendments are depth-dependent and mediated by climatic and soil properties. All three amendments significantly increased SOC in both topsoil and subsoil. In topsoil, straw (+29.4%, +10.1%), biochar (+120%, +27.4%), and organic fertilizers (+54.9%, +16.6%) increased both POC and MAOC, but the disproportionate increases between the two fractions reduced SOC stability. In subsoil, straw and organic fertilizers promoted balanced increases in POC and MAOC without compromising carbon pool stability, whereas biochar primarily increased POC with minimal impact on MAOC and SOC stability. These findings underscore the critical role of amendment type in regulating carbon fractions across soil depths. Tailoring organic amendment strategies to local climate and soil conditions is essential for optimizing SOC sequestration efficiency and long-term stability.

**Keywords:** Soil organic carbon; Particulate organic carbon; Mineral-associated organic carbon; Soil organic carbon stability; Meta-analysis

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# A systematic analysis and review of soil organic carbon stocks in urban greenspaces

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**ABSTRACT**

Urban greenspaces typically refer to urban wetland, urban forest and urban turfgrass. They play a critical role in carbon sequestration by absorbing carbon from the atmosphere; however, their capacity to retain and store carbon in the form of soil organic carbon (SOC) varies significantly. This study provides a systematic analysis and review on the capacity of different urban greenspace types in retaining and storing SOC in 30 cm soil depth on a global scale. Data came from 78 publications on the subject of SOC stocks, covering different countries and climate zones. Overall, urban greenspace types exerted significant influences on the spatial pattern of SOC stocks, with the highest value of 18.86 ± 11.57 kg $m^{-2}$ (mean±standard deviation) in urban wetland, followed by urban forest (6.50 ± 3.65 kg $m^{-2}$), while the lowest mean value of 4.24 ± 3.28 kg $m^{-2}$ was recorded in urban turfgrass soil. Soil organic carbon stocks in each urban greenspace type were significantly affected by climate zones, management/environmental settings, and selected soil properties (i.e. soil bulk density, pH and clay content). Furthermore, our analysis showed a significantly negative correlation between SOC stocks and human footprint in urban wetland, but a significantly positive relationship in urban forest and urban turfgrass. A positive correlation between SOC stocks and human footprint indicates that increased human activity and development can enhance SOC stocks through effective management and green infrastructure. Conversely, a negative correlation suggests that improper management of human activities can degrade SOC stocks. This highlights the need for sustainable practices to maintain or enhance SOC accumulation in urban greenspaces.

**Keywords:** Soil organic carbon; Vegetation type; Human footprint; Climate; Selected soil properties; Management and environmental setting

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# Nitrogen addition effects on soil organic carbon accrual in cropland land

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**ABSTRACT**

Initiatives to restore soil fertility and mitigate global warming rely on rebuilding soil organic carbon (SOC). Nitrogen (N) fertilization is crucial for crop yields but affects SOC unpredictably due to varying responses of particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) pools to initial SOC levels. To clarify these effects, here, by combining a global meta-analysis with continental-scale field experiments, we determine that an initial SOC threshold of 15 g C kg−1 controls the effect of N fertilization on POC and MAOC. In SOC-poor soils (< 15 g C kg−1), N fertilizer increases plant-derived C inputs and promotes soil aggregation, favouring POC accumulation. Conversely, in SOC-rich soils, N fertilizer stimulates microbial metabolic efficiency, leading to larger necromass production and stabilization by mineral protection, observed as more pronounced MAOC accrual. Our findings reveal how SOC thresholds shape the response of active and stable carbon pools to N fertilization, with consequences for SOC accrual in cropland soils globally.

**Keywords:** Nitrogen, Soil organic carbon, Particulate organic carbon, Mineral-associated organic carbon, microbial necromass

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# Quantifying soil organic matter effects on nitrogen use efficiency and fate in wheat-maize cropping systems: a $^{15}N$ tracer approach

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## ABSTRACT

Soil organic matter (SOM) is a recognized determinant of nitrogen use efficiency (NUE), but its quantitative control over the fate of fertilizer N remains unclear. Using a $^{15}N$ tracer study within a winter wheat-summer maize rotation, we quantified the recovery of initially applied-N from wheat and subsequent crops in relation to SOM and N-application rates. We found that while N fertilization boosted yields by 85-340% in low-fertility soil, its effectiveness exhibited diminishing returns in high-fertility soils. Crucially, the total recovery efficiency of fertilizer N (cumulative $^{15}NUE$) across three cropping seasons was fundamentally governed by SOM content, following a linear-plateau relationship. The model revealed that maximum $^{15}NUE$ (54.3%) at an optimal application rate (105 kg N $ha^{-1}$) was achieved when SOM exceeded a critical threshold of 21.3 g $kg^{-1}$. Below this threshold, $^{15}NUE$ declined linearly with SOM. Furthermore, residual $^{15}N$ in soil was primarily stabilized in organic forms (58-64%), while recovery by subsequent crops was minimal (≤4.3%), confirming that high SOM minimizes environmental N losses by enhancing sequestration in the soil organic pool. Our findings establish a quantifiable SOM threshold for maximizing NUE, providing a science-based pathway to reduce fertilizer waste and enhance sustainability in intensive agriculture.

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# Phosphorus as the key driver: Long-term fertilization unlocks nonlinear gains in nitrogen recovery efficiency in Chinese croplands

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## ABSTRACT

Nitrogen recovery efficiency (NRE) is a critical metric for minimizing environmental pollution and ensuring sustainable agriculture. However, its long-term dynamics and underlying drivers remain poorly understood. This study synthesizes data from a 30-year positioning experiment across four key agricultural regions in Northern China to analyze the spatiotemporal evolution of NRE under varied fertilization regimes. Using nonlinear modeling, random forest analysis, and structural equation modeling, we identified the patterns, dominant factors, and mechanistic pathways governing NRE. Key findings revealed that NRE followed a significant nonlinear trajectory over time. Long-term balanced fertilization-particularly the integrated NPKM treatment-consistently enhanced NRE in the later experimental phase (2006-2020), whereas imbalanced fertilization (N-only or NK) led to a marked decline. Soil properties emerged as the primary drivers of NRE variation, with available phosphorus (AP) identified as the key limiting factor. Below a threshold of 22.3 mg $kg^{-1}$, NRE increased sharply with rising AP, reaching up to 59.9%. Notably, grain yield plateaued (8.31 tonnes $ha^{-1}$) only when AP exceeded 29.0 mg $kg^{-1}$, and regional AP thresholds for optimal NRE varied widely (19.0-48.8 mg $kg^{-1}$). Fertilization indirectly influenced NRE by modifying soil nutrient status and interacting with climate, while crop yield exerted a direct, crop-specific effect-positive in maize but negative in wheat seasons.

In conclusion, long-term balanced fertilization nonlinearly enhances NRE by alleviating P limitation and improving soil function. By integrating regional AP thresholds and crop-specific responses, this research provides a scientific basis for spatially tailored nutrient management, supporting the dual goals of agricultural productivity and environmental sustainability.

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# Organic fertilization under conservation tillage enhances biopore formation and particulate organic matter accumulation via fraction-specific pore relationships in a Vertisol

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## ABSTRACT

Understanding how fresh, decomposed, and root-derived particulate organic matter (POM) interact with soil macropores is crucial for enhancing soil organic carbon stocks, yet their spatial relationships remain largely unclear. Therefore, we conducted an 8-year conservation tillage experiment on a Vertisol (wheat-maize rotation, no tillage with straw return) that compared four fertilization regimes: (i) control (no fertilization), (ii) chemical fertilization (NPK), (iii) organic fertilization (OF), and (iv) combined chemical-organic fertilization (NPKOF). X-ray computed tomography was used to quantify POM fractions (fresh POM: FPOM, decomposed POM: DPOM, root-derived POM: RPOM), macropore and biopore structure. Our results demonstrated that all fertilization treatments (NPK, OF, NPKOF) significantly improved soil macropore structure in the 0-10 cm layer, whereas OF and NPKOF increased bioporosity by 4.82-fold and 2.26-fold in the 10-20 cm layer ($P<0.05$). Biopores constitute a major component of percolating pores in the subsoil and are promoted by the application of organic fertilization. Furthermore, OF and NPKOF significantly enhanced fresh POM and root-derived POM content in the 0–10 cm layer and shortened their distance to pores throughout the 0–20 cm layer ($P<0.05$). The three POM fractions exhibited positive correlations with macropore structure characteristics ($P<0.05$), yet no significant correlation was observed between root-derived POM and biopores. Root-derived POM showed preferential accumulation in areas distant from biopores. Overall, our findings demonstrate that long-term organic fertilization is linked to increased POM accumulation, improvements in surface soil macropore structure, and enhanced biopore formation in the subsoil of Vertisols.

**Keywords:** Soil macropore structure; Biopore; Particulate organic matter (POM); Organic fertilization; X-ray CT; Vertisol; Conservation tillage

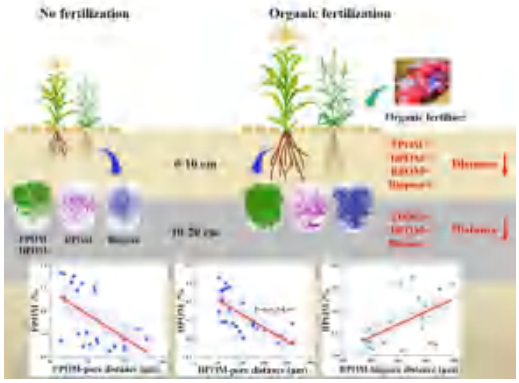



Figure Conceptual diagrams illustrating the spatial distribution of POM fractions and pores under organic fertilizer application.

**Acknowledgments**

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# Simulation of the evolution of cropland soil organic carbon in the Tuojiang River Basin over the past century

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**ABSTRACT**

Accurately quantifying long-term dynamics of cropland soil organic carbon (SOC) is essential for elucidating the fundamental mechanisms controlling SOC. SOC process-based models provide an effective framework for reconstructing historical SOC dynamics and projecting future trajectories. The AMG model relies on a small number of readily available inputs and has been applied and validated across diverse cropping systems and soil–climate conditions, making it an effective tool for simulating cropland SOC dynamics over long time periods and large spatial scales.

In this study, the Tuojiang River Basin, a traditional agricultural region in southwestern China, was selected as the case study area. Long-term data from permanent experimental stations (13–27 years) were first used to evaluate the applicability of the AMG model with default parameters. After calibrating the initial $C_S/C_0$ ratio and the potential mineralization rate ($k_0$), the accuracy of simulated cropland SOC stocks improved substantially ($R^2 = 0.87$, RMSE = 0.25, d = 0.90), representing a 23% increase in $R^2$ and a 35% reduction in RMSE compared with the default parameterization (Fig. 1). Multi-scale independent validation further confirmed the robust performance of the improved AMG model at the regional scale.

The improved AMG model, combined with historical spatially explicit input factors, was then applied to analyze century-long cropland SOC dynamics and their driving mechanisms. From 1911 to 2017, cropland SOC stocks increased from 31.2 to 46.9 t C $ha^{-1}$, corresponding to a 50.2% increase (Fig. 2). SOC stocks increased slowly before the 1960s and rose rapidly after the 1980s. Pronounced latitudinal differentiation was observed across the basin, with consistently higher SOC stocks in the upstream Chengdu Plain and lower values in downstream hilly regions. After 1980, the midstream area emerged as a hotspot of SOC accumulation. Between 1911 and 2017, SOC stocks increased by more than 50% in downstream areas such as Zigong and Renshou, whereas increases were below 40% in upstream counties of the Chengdu Plain, including Pengzhou and Jingyang (Fig. 3). Counterfactual scenario simulations indicate that the century-scale increase in cropland SOC was primarily driven by changes in crop residue carbon inputs. Since the 1960s, the widespread use of chemical fertilizers has substantially enhanced crop yields and played a key role in SOC accumulation, while the contribution of climate change to SOC increases was relatively small. Notably, in the upstream Chengdu Plain, interactions between cropland carbon inputs and climate change exerted a significant influence on SOC dynamics. The results offer scientific support for improving cropland soil carbon management in other comparable traditional agricultural regions.

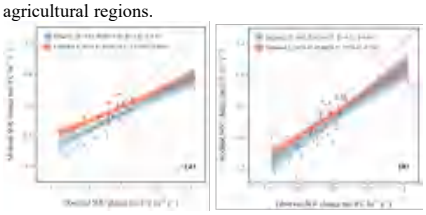


**Fig. 1.** The scatter plot of observed and simulated soil organic carbon stock for 14 LTEs based on the (a) default $C_S/C_0$ size (with default $k_0 = 0.29\ yr^{-1}$ and calibrated $k_0 = 0.193\ yr^{-1}$) and (b) $PARTY_{SOC}$-based $C_S/C_0$ initialization (with default $k_0 = 0.29\ yr^{-1}$ and calibrated $k_0 = 0.209\ yr^{-1}$) applying leave-one-site-out cross validation for all sampling dates at the 14 long-term experiment sites.

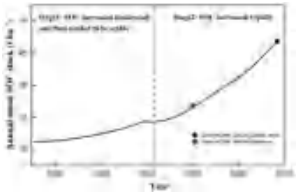


**Fig. 2.** Modelled (line) temporal variations in annual mean cropland SOC stock density in the Tuojiang River Basin simulated using the AMG model. The black and red dots represent the observed SOC stock density.



**Fig. 3.** Spatial distribution of cropland SOC stocks at a 1 km resolution from 1911 to 2017 with unchanged cropland distribution

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# Fertilizer-N recovery links to SOC stabilization and fractionation in straw-mulched soil: Insights from $^{15}$N-tracing and $^{13}$C natural abundance

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**ABSTRACT**

While straw mulching has the potential to reduce fertilizer-nitrogen (N) losses in intensively managed cropland, how soil organic carbon (SOC) regulates this fate of fertilizer-N at soil aggregate or profile scales remains unresolved. Here, micro-plots were nested within a four-year field experiment to assess fertilizer-N fates and their linkages with SOC fractions and stabilization processes via $^{15}$N-tracing and $^{13}$C natural abundance analyses. Three treatments were included: (i) conventional N application (FN), (ii) reduced N application (RN), and (iii) reduced N with straw mulching (RS). While RN reduced crop yields compared to FN, RS achieved comparable yields and 7.71% higher N recovery efficiency ($P$<0.05). The $\delta^{13}$C fractionation between aggregates and bulk soil was significantly positively correlated with the fertilizer-N content in the >2 mm and <0.053 mm fractions, indicating that N retention was coupled with SOC stabilization processes. Compared with RN, RS resulted in a 2−3.4 times greater SOC conversion probability into the <0.053 mm fraction and a 1.4 times higher aggregate-associated fertilizer-N content. SOC fractions differentially regulated the profile distribution of fertilizer-N, with nonlabile organic carbon (C) correlated positively, while dissolved organic C correlated negatively but increased plant N recovery. Compared with RN, RS increased the SOC stock by 24%, reduced $NO_3^-$-N accumulation by 37%, and immobilized 36% more N into the microbial biomass ($P$<0.05). Our findings demonstrate that straw mulching increases N recovery by mediating SOC fractionation, stabilization, and microbial N immobilization. These results provide new insights into SOC–N interactions that could aid in the development of optimal soil C and N management strategies.

**Acknowledgments**

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# Mechanisms of soil organic carbon sequestration within aggregates of black soil under long-term land use change

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**ABSTRACT**

Evaluation of soil organic carbon (SOC) dynamics is often constrained by the structural and compositional complexity of the soil matrix. Quantifying the distribution of SOC across aggregate hierarchies is therefore essential for elucidating carbon transfer and stabilization processes within soils, yet such information remains limited. Both the amount and chemical composition of aggregate-associated organic carbon are critical determinants of SOC stability. In addition, soil aggregates function as key microhabitats that structure microbial communities and regulate carbon sequestration. However, the mechanisms linking microbial community assembly and carbon stabilization across aggregate fractions under long-term land-use change remain poorly resolved.

A 35-year field experiment in Northeast China was used to examine the effects of contrasting land uses (cropland, bare land, forestland, and grassland) on soil aggregate structure, microbial diversity, and carbon sequestration potential in a black soil. Soil aggregates were separated by combined wet- and dry-sieving into large macroaggregates (>2 mm), macroaggregates (2–0.25 mm), and microaggregates (<0.25 mm) to quantify aggregate size distribution and stability (water- and mechanically stable aggregates). By integrating FTIR-based characterization of organic carbon chemistry, phospholipid fatty acid (PLFA) analysis, 16S rRNA and ITS sequencing, and PICRUSt2-inferred functional potentials, the biogeochemical mechanisms governing aggregate-associated carbon sequestration following ecosystem transitions were elucidated.

The results highlight the importance of coupled biological–chemical interactions within soil aggregates in regulating long-term SOC stabilization. This study provides a mechanistic framework linking soil microstructure, microbial assembly, and carbon sequestration, thereby contributing to improved multi-scale modeling of soil carbon cycling and offering guidance for sustainable land-use management in black soil regions.

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2. Na Li*. Long-term land use patterns shaped soil microbial community effects on organic carbon sequestration within aggregate (in draft)

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# Contrasting effects of long-term fertilization on pore structure and POM in upland and paddy soils revealed by X-ray CT

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## ABSTRACT

Soil pore structure plays a fundamental role in particulate organic matter (POM) dynamics by regulating water and air exchange within the soil matrix. However, the effects of long-term fertilization on POM distribution, pore characteristics, and their interrelationships may differ between upland and paddy soils. In this study, we examined two long-term fertilization field experiments conducted in contrasting agroecosystems in Jiangxi, China: a 38-year upland field and a 43-year paddy field. Four fertilization regimes were compared: no fertilizer (control), inorganic fertilizer (NPK), double-rate inorganic fertilizer (2NPK), and inorganic fertilizer combined with pig manure (NPKM). X-ray computed tomography (CT) was used to quantify soil pore structure and POM, and machine learning-based image analysis was applied to classify POM into fresh and decomposed fractions based on morphological features. The NPKM treatment significantly increased fresh and decomposed POM volume density by 2.05% and 47.7% in upland soil, and 253% and 103% in paddy soil, respectively ($P$<0.05). NPKM also enhanced air permeability ($K_a$) image-based porosity, connected porosity, >300 μm porosity, and surface area density in both soils ($P$<0.05). In upland soil, strong positive correlations between fresh POM and pore structure parameters suggest a close association between organic matter input and physical structure. In paddy soil, pore structure facilitates the retention of root-derived fresh POM under anaerobic conditions. Overall, our findings demonstrate that long-term manure application promotes both POM accumulation and the development of pore structure in upland and paddy soils, with distinct mechanisms operating under different land-use systems.

**Keywords:** Red soil; manure application; particulate organic matter; pore structure; X-ray computed tomography; Long-term agroecosystem

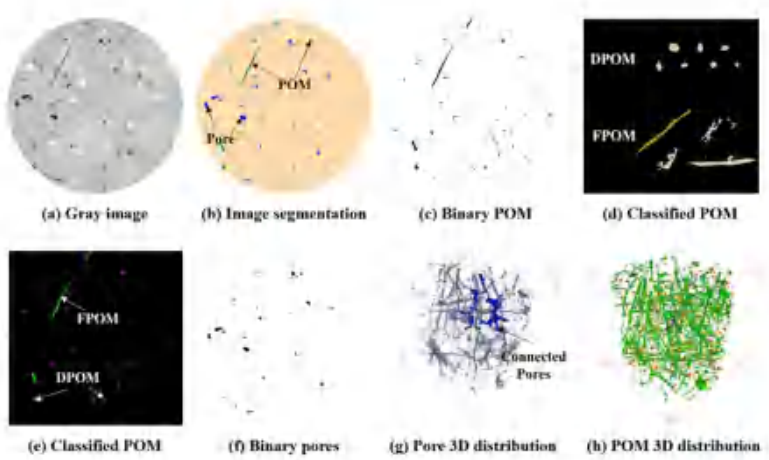



Figure Visualization and quantification of POM fractions and pore structures.

**Acknowledgments**

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# Socioeconomic development and cropland projects reversed soil carbon loss across the whole cropland profile: Evidence from China

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**ABSTRACT**

Climate warming exerts positive feedback on soil carbon loss throughout the whole soil profile. Cropland soils hold substantial carbon sequestration potential and play a crucial role in global climate change mitigation and terrestrial ecosystem carbon cycling. Since the 1980s, China has undergone rapid socioeconomic development and implemented extensive land consolidation projects, leading to significant changes in cropland soil organic carbon (SOC). However, the dynamics of SOC across the whole soil profile and their driving mechanisms remain unclear. To address this, we utilized 519 cropland soil profiles (0-1 m, 20 intervals) excavated in 2020 and 234 historical data from the Second National Soil Survey in the 1980s to examine changes in SOC content across the whole profile in China's warm temperate croplands. By integrating machine learning and Partial Least Squares Path Modeling (PLS-PM), we further explored the mechanisms driving SOC changes. Results showed that over the past four decades, SOC at 1 m depth increased by 0.95 g C $kg^{-1}$, corresponding to an SOC stock gain of 14.88 t C $ha^{-1}$-enough to offset 33% of regional cropland carbon emissions. The increase was more pronounced in surface soils than in deeper layers, resulting in a steeper vertical SOC gradient. Soil physicochemical properties emerged as the dominant drivers of SOC variation across the whole profile. The direct influence of climate has weakened over time, its effects have intensified with increasing soil depth. Socioeconomic development and cropland management projects significantly enhanced carbon inputs via increased crop residues, thus promoting SOC accumulation particularly in surface soils. Over time, the net effect of socioeconomic factors and land governance on SOC has shown the largest increase. Our findings highlight that the coordinated advancement of socioeconomic development and land consolidation has driven the enhancement of SOC across the whole soil profile, mitigating carbon losses induced by climate change. This provides new empirical evidence for reversing global soil carbon loss under current warming scenarios.

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# Microbial necromass outperforms the chemical stability of SOC in predicting soil multifunctionality under 44-year of organic amendment in red paddy soil

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## ABSTRACT

Red paddy soils are widely distributed in the subtropical regions of China and have long been confronted with issues such as acidification, aluminum toxicity, and organic matter depletion, which constrain the synergistic enhancement of soil multifunctionality. Although the application of organic materials has been proven to mitigate soil degradation, the long-term biogeochemical mechanisms through which they regulate soil multifunctionality remain unclear. This study is based on a 44-year field experiment on a red paddy soil, aiming to evaluate the soil physicochemical properties, organic carbon chemical structure, microbial necromass carbon, and microbial community composition under different organic material applications. The goal is to reveal the response characteristics of soil multifunctionality to long-term organic material application and its key regulatory pathways. The results showed that long-term organic material application significantly increased soil organic carbon content and altered its chemical structure, with the aliphaticity in the pig manure treatment decreasing by 5.11% compared to the Control. Furthermore, compared to the Control, the pig manure treatment increased bacterial, fungal, and total microbial abundances by 66.86%, 96.84%, and 79.66%, respectively. It also increased bacterial necromass carbon, fungal necromass carbon, and total microbial necromass carbon content, and significantly enhanced soil multifunctionality, with the pig manure treatment showing a particularly prominent effect-increasing by 169.53% compared to the Control. Further analysis revealed that soil organic carbon, total nitrogen, total phosphorus, microbial abundance, and microbial necromass carbon were the main factors driving soil multifunctionality, rather than the chemical structure of soil organic carbon. Our findings provide important theoretical and empirical foundations for organic carbon sequestration and sustainable management of red paddy soils.

**Keywords:** Organic amendments; Red paddy soil; Soil microorganisms; Organic carbon chemical structure; Soil multifunctionality

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# Straw-decomposing inoculants strengthen the mitigation effect of straw on $N_2O$ emissions via synergistically inhibiting the abundance and activity of AOB in a wheat field

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**ABSTRACT**

The application of straw-decomposing inoculants has been demonstrated to accelerate straw decomposition and reduce soil nitrous oxide ($N_2O$) emissions in fields incorporated with straw. However, the mechanisms underlying $N_2O$ emission mitigation following decomposing inoculant application remain unclear. A two-year field experiment was conducted in a subtropical wheat cropping system to elucidate key factors regulating $N_2O$ emissions under straw and straw-decomposing inoculant application. The autotrophic nitrification driven by ammonia-oxidizing bacteria (AOB) and archaea (AOA) was quantitatively partitioned using acetylene and 1-octyne inhibition techniques. Applying straw or decomposing inoculants alone significantly reduced yield-scaled $N_2O$ emissions by 39.75% and 35.83%, respectively. The combined application showed a significantly greater reduction effect (46.47%). Decomposing inoculants promoted wheat plant growth and increased total nitrogen (TN) contents in both straw and grain. AOB dominated nitrification-related $N_2O$ production, while straw, decomposing inoculant, and their combinations significantly decreased AOB-mediated contributions by 9.19%, 7.63%, and 11.23%, respectively. In contrast, straw markedly enhanced the abundances of *nosZI* and *nosZII* genes. Structural equation modeling (SEM) suggested that the decreased $N_2O$ emissions under the combination of straw and decomposing inoculants were synergistically linked to the inhibited abundance of AOB and the enhanced abundances of *nosZI* and *nosZII*. These results suggested that the straw-inoculant combination achieves a concurrence of crop yield enhancement and $N_2O$ emissions reduction, representing a win-win strategy for supporting food security and China's "Dual Carbon" policy.

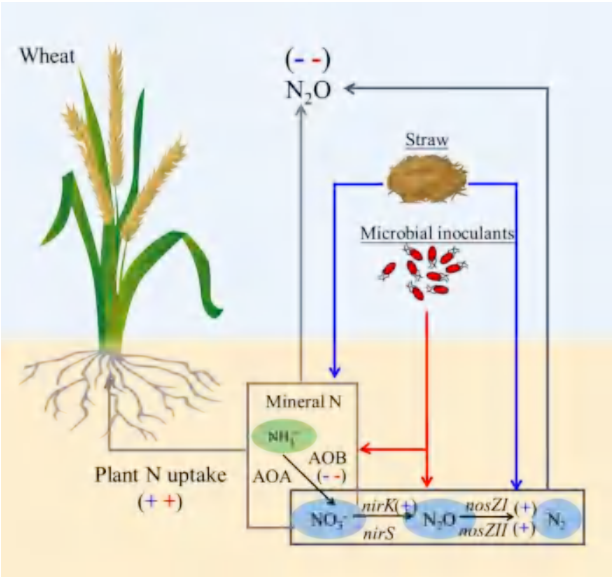



Fig.1 Graphical ABSTRACT

# Evolutionary Characteristics of Stable Organic Matter in Lateritic Red Soils under Long-Term Rotation and Fertilization Systems

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**ABSTRACT**

Soil stable organic matter serves as the foundation of soil fertility and an indicator of carbon sequestration capacity. Crop rotation and fertilization are practices involving intense and frequent soil disturbance, which inevitably exert significant impacts on stable organic matter. From 2009 to 2024, soil samples were collected from a long-term experimental station (over 15 years) in the lateritic red soil region of China for this study. These samples encompassed different rotation systems—specifically, double-cropping rice, continuous vegetable cultivation, vegetable-vegetable-rice rotation, and a natural uncultivated plot—and various fertilization practices, including no fertilization (CK), chemical fertilizer only (CF), organic fertilizer only (OF), combined organic and inorganic fertilization (CF+OF), and chemical fertilizer with rice straw retention (CF+Straw). The study focused on: (1) the variation processes and differences in soil organic matter fractions; (2) the chemical composition and dynamics of the mineral-associated organic matter (MAOM), representing the stable organic matter pool; and (3) the proportional sources and their evolution of MAOM. The results indicated that the natural uncultivated plot exhibited the highest annual increase rate of SOM. Under the double-cropping rice system, the annual SOM increase rates across fertilization treatments followed the order: OF > CF+OF > CF+Straw > CF > CK. In contrast, for both the vegetable-vegetable-rice rotation and continuous vegetable cultivation systems, only the CF+OF led to positive soil organic carbon sequestration. The sequestration of soil organic matter observed above was primarily driven by a steady increase in particulate organic matter, while the MAOM content remained relatively stable. The chemical composition and proportional sources of MAOM have been determined and are currently being analyzed.This work is expected to provide a theoretical foundation and scientific basis for breakthroughs and innovations in organic matter stabilization technologies in lateritic red soils in South China.

**Acknowledgments**

This study is supported by Guangzhou Field Scientific Observation and Research Station of Soil Quality and funded by the Natural Science Foundation of China (42307455) and the Guangdong Basic and Applied Basic Research Foundation (2024A1515010270).

# Nitrogen fertilization enhances straw carbon sequestration in reclaimed mine soils by regulating microbial community stability and function

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## ABSTRACT

Reclaimed soils in coal gangue backfilling areas are characterized by low productivity and critically low soil organic carbon (SOC). While straw return is a recommended strategy to increase SOC, its high carbon to nitrogen (N) ratio can exacerbate microbial N limitation in these inherently N poor soils. This may trigger a positive priming effect and hence accelerate the loss of native SOC and reduce overall C sequestration efficiency.

This study investigated how N addition modulates SOC dynamics during maize straw return in a 5-year long term reclamation experiment. Results showed that straw return combined with N fertilization—optimally at 270 kg N $ha^{-1}$—significantly increased SOC content, compared to at 216 or 180 kg N $ha^{-1}$ N rate. Nuclear magnetic resonance analysis indicated a concurrent shift toward more stable SOC forms, with increased polysaccharide C, methyl C, aromatic C, carboxyl C, and aliphatic C. Furthermore, tracking amino sugars as microbial necromass biomarkers revealed that high N treatment promoted the accumulation of microbial derived residues, which after 500 days contributed 69.6% to total SOC, with fungal residues being dominant.

High throughput sequencing demonstrated that high N fertilization reduced variability in bacterial and fungal communities by 8.5% and 12.3%, respectively, and lowered bacterial diversity, indicating enhanced community stability. Network analysis revealed stronger fungal bacterial interactions and increased network robustness under 270 kg N $ha^{-1}$. Metagenomic analysis showed a marked enrichment in carbohydrate active enzyme (CAZyme) genes, particularly those involved in cellulose and hemicellulose degradation, pointing to a more efficient microbial straw degradation capacity.

A partial least squares path model identified soil nutrient status as the key driver of microbial community assembly, which in turn regulated the abundance of fungal and bacterial CAZyme genes. Among SOC components, methyl C explained the largest proportion of variation in CAZyme gene abundance, whereas aliphatic C and aromatic C showed no significant correlation, highlighting functional differences among C forms.

In summary, straw return combined with the proposed optimal N fertilization not only elevates SOC content but also enhances its chemical stability in reclaimed-mine soils. Nitrogen facilitates the conversion of straw or organic C into stable, microbial derived C pools by stabilizing microbial community structure, strengthening interspecific interactions, and activating key decomposition pathways. These findings clarify the essential role of N management in straw-based reclamation and provide a thermotical and practical basis for improving soil fertility and C sequestration in post mining landscapes.

**Acknowledgments**

This research was supported by the Major Science and Technology Special Project in Shanxi Province Unveiled Projects (202201140601028), the Shanxi Basic Research project (202303021212104), and Open Research Projects of the Engineering Technology Innovation Center for Ecological Protection and Restoration in the Middle Yellow River, Ministry of Natural Resources (20250007, 2025078).

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# Distribution Characteristics and Influencing Factors of Carbon and Nitrogen Content in Mineral-Associated Organic Matter in Mollisols (Phaeozems) of Northeast China

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**ABSTRACT**

Mineral-associated organic matter (MAOM) is a stable component of soil organic matter (SOM). The carbon and nitrogen contents in MAOM vary under different land use types, while their distribution characteristics and influencing factors under tillage remain poorly understood. In this study, we collected 30 pairs of cropland and natural topsoil samples from Mollisols in Northeast China along a latitudinal gradient from south to north to investigate how mineral-associated organic carbon (MAOM-C) and mineral-associated organic nitrogen (MAOM-N) responds to land use changes in the Mollisols region. We found that MAOM-C content in cropland soils (mean 33.4 $mg \cdot g^{-1}$ soil; ranging from 8.8 to 57.3 $mg \cdot g^{-1}$) is higher than in natural soils (mean 27.3 $mg \cdot g^{-1}$; range 6.9 to 58.0 $mg \cdot g^{-1}$). In contrast, MAOM-N content was higher in natural soils (mean 2.3 $mg \cdot g^{-1}$; range 1.1 to 5.1 $mg \cdot g^{-1}$) than in cropland soils (2.1 $mg \cdot g^{-1}$; 1.2-4.9 $mg \cdot g^{-1}$). MAOM-C and MAOM-N contents in both types of soils exhibit an increasing trend from south to north, due to greater soil organic carbon (SOC) content further north. However, cropland soils—especially those south of 47°N—exhibited a greater proportion of C and N from MAOM in SOM than those in natural soils. This pattern was mostly due to cultivation-induced soil disturbance and elevated temperatures in the south, which may lead to the preferable loss of POM in these soils. Our partial least squares structural equation modeling (PLS-SEM) results showed that temperature had a negative correlation with both MOAM-C and MAOM-N, whereas MAOM-C and MAOM-N were positively correlated with SOC. When natural land is converted into cropland, the effect of soil carbon-to-nitrogen (C/N) ratio on MAOM-C and MAOM-N shifts from being positive to negative, suggesting that, under the influence of tillage disturbance, the C/N ratio becomes the key factor regulating MAOM content. The C/N ratios in MAOM are higher than ones in SOM for both types of soils in the north, suggesting more plant-derived OM being incorporated into MAOM there. Overall, our study demonstrates that MAOM dynamics in Mollisols are controlled by land use and climate, and further modulated by a latitudinal shift in the dominant source of organic matter: plant-derived compounds become increasingly important toward the north, indicating region-specific formation pathways and stabilization mechanisms of SOM.

**Acknowledgments**

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# Long-term organic farming alters soil organic matter molecular composition through divergent microbial processing pathways

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**ABSTRACT**

While organic farming is acknowledged as a potential pathway to boost soil fertility and other functionalities, the underlying mechanisms by which it affect the biochemistry of soil organic matter (SOM) are not yet clear. To fill this knowledge gap, we sampled soils from 0–20 cm layer from three 20-year of fertilization practices in North China: conventional (CON), integrated (INT), and organic farming (ORG). Then, targeted SOM molecular fingerprints were quantified by utilizing three biomarkers such as free lipids, lignin phenols, and amino sugars, along with extracellular enzyme activities. The results showed that ORG increased soil organic carbon (SOC), particulate organic carbon (POC), and mineral-associated organic carbon (MAOC) contents by 101.6%, 231.5%, and 28.4%, respectively, compared to CON. In contrast, ORG (cf. CON) enhanced both microbial-derived lipids (short-chain lipids, $< C_{20}$) and plant-derived lipids (long-chain lipids, $\geq C_{20}$) by 48.9% and 112.3%, while also accelerating aliphatic lipids degradation. Compared with CON, ORG increased lignin phenols by 58.4% and reduced their degree of degradation. In addition, ORG (cf. CON) increased microbial-derived biomolecules, including bacterial (+63.6%), fungal (+71.5%), and microbial necromass C (+66.9%), without altering its relative contribution to SOC. Furthermore, ORG increased hydrolytic enzymes activities, and microbial carbon use efficiency (CUE). Overall, our study highlights that two decades of organic farming promote SOC accumulation through the enhancement of plant- and microbially-derived carbon and microbial carbon processing, providing new mechanistic insights into the soil microbial carbon pump under long-term organic management.

# Spatiotemporal Spectral Reconstruction for Soil Organic Matter Mapping under Complex Cropland Surface Conditions

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**ABSTRACT**

Soil Organic Matter (SOM) is a critical indicator of soil health and a key component of the global carbon cycle. High-resolution digital soil mapping is essential for precision agriculture and carbon sequestration assessment. However, in intensive agricultural regions such as the North China Plain (NCP), the accuracy of optical remote sensing is severely hindered by the spatiotemporal heterogeneity of soil moisture and the masking effects of crop residues (e.g., straw) under conservation tillage practices. Traditional methods, which rely on single-temporal images or simple vegetation indices masking, often fail to effectively decouple these complex surface interferences, leading to significant uncertainties in SOM retrieval. To address these challenges, this study proposes a novel Spatiotemporal Spectral Reconstruction Framework that integrates time-series analysis with spatial unmixing. First, at the temporal dimension, we developed a Minimum Soil Moisture (MinSM) synthesis strategy. By leveraging the Soil Moisture Index (SMI) across the full Sentinel-2 time series, this method identifies and composites the spectral reflectance of the driest soil state for each pixel, thereby minimizing moisture-induced spectral attenuation and noise. Second, at the spatial dimension, we introduced a Spectral Unmixing Model based on the reflectance-vegetation coverage feature space. This model dynamically separates pure soil signals from mixed pixels containing crop residues and green vegetation, effectively recovering the soil background spectra in high-residue areas. The proposed framework was validated using 350 topsoil samples collected from the NCP and Sentinel-2 imagery. The results demonstrated that the reconstructed soil spectra achieved high prediction accuracy for SOM, with a coefficient of determination ($R^2$) of 0.83 and a Root Mean Square Error (RMSE) of 2.59 g/kg, significantly outperforming traditional median synthesis and masking methods. Based on this approach, we generated a 10-m resolution annual SOM dataset for the study area from 2015 to 2025. The spatiotemporal analysis revealed a distinct "North-high, South-low" distribution pattern, closely driven by long-term straw return policies. This study provides a robust, transferable paradigm for extracting accurate soil information in complex, human-altered agricultural landscapes.

**Acknowledgments**

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# Long-term Grassland Conversion Reshapes Deep Soil C and N Cycling: Thermodynamic Destabilization and Microbial Drivers

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**ABSTRACT**

The conversion of natural grassland to cropland significantly impacts global carbon and nitrogen cycles, yet the long-term, depth-dependent mechanisms regulating these pools remain poorly constrained. This study utilized a chronosequence in Hulunbuir, China, comparing natural grassland with 11- and 40-year cultivated croplands to assess changes in soil organic carbon (OC), nitrogen (N), and dissolved organic matter (DOM) across a 1-meter profile. By integrating high-resolution molecular techniques (FT-ICR-MS), microbial functional gene quantification, and thermal incubation experiments, the study aimed to uncover the biogeochemical drivers of soil stability under land-use change. Results indicated a severe subsoil crisis following conversion, with total N losses reaching 83.6% in deep soils (80–100 cm) after 40 years. Unexpectedly, this depletion was driven by losses in mineral-associated organic matter, typically considered stable. While topsoil OC stabilized over time, subsoil DOM paradoxically accumulated but became thermodynamically unstable, characterized by lower Gibbs free energy and increased microbial processing. Regarding N cycling, medium-term cultivation enhanced nitrification, whereas long-term farming suppressed it, reducing plant-available N. Crucially, land-use change altered thermal sensitivity: agricultural soils showed increased temperature sensitivity for OC decomposition and, under warming conditions, subsoils shifted from acting as nitrous oxide sinks to net sources. These shifts were underpinned by a restructuring of microbial functional gene networks, which exhibited greater complexity in the subsoil. In conclusion, multidecadal agricultural conversion fundamentally destabilizes deep soil C and N reservoirs and heightens vulnerability to climate warming, necessitating sustainable management strategies that prioritize subsoil stability.

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# Optimizing and simulating the soil carbon fractions within the BEPS-MEND framework

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**ABSTRACT**

Terrestrial ecosystems are important carbon sinks and regulate variations in atmospheric carbon dioxide ($CO_2$) concentrations. Accurate estimation of ecosystem carbon fluxes is essential for assessing ecosystem carbon balance and addressing climate change. Ecosystem process-based models are effective tools for simulating carbon fluxes at different spatiotemporal scales. However, existing models still face challenges including high parameter uncertainty, incomplete process mechanisms, and a lack of representation on soil organic carbon fractions. This study is based on the BEPS (Biosphere Exchange Processes Simulator) model, coupled with the MEND (Microbial Enzyme-Mediated Decomposition) microbial enzyme-mediated decomposition carbon pool module, and combined with soil organic carbon fraction data collected, to conduct regional-scale simulations of carbon fluxes in different ecosystems across China. This study will optimize parameters related to key ecological processes such as photosynthesis and soil microbial decomposition, reveal potential relationships between different processes, and explore variation trends of carbon fluxes in regions with different vegetation types in China. The optimized carbon flux simulation framework constructed in this study, which is suitable for complex ecosystems in China, will reveal spatiotemporal co-evolution patterns of key ecological processes and provide dynamic process analysis tools and a scientific basis for decision-making to enhance bottom-up terrestrial carbon sink estimation capabilities, and support the formulation of terrestrial carbon sink management policies under the carbon peaking and carbon neutrality strategic goal.

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# Exploring Aerobic Methanotroph Diversity in Terrestrial Habitats: Recent Advances and Challenges for Further Studies

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**ABSTRACT**

Aerobic methanotrophic bacteria play a key role in the cycling of the potent greenhouse gas methane ($CH_4$) in terrestrial habitats. Despite the century-long history of studying methanotrophs, these bacteria remain an inexhaustible source of exciting discoveries. These include earlier unknown phenotypes of methanotrophic bacteria, new features of their metabolic organization, and novel aspects of their environmental importance. One of the important recent research directions was focused on USCα methanotrophs, which are the key component of the methane-oxidizing communities responsible for atmospheric $CH_4$ oxidation in a number of terrestrial ecosystems, such as the subarctic and arctic tundra, forested subarctic tundra as well as boreal upland soils. The use of novel cultivation strategies resulted in obtaining representative isolates of *Methylocapsa*-affiliated methanotrophic bacteria from subarctic soils. These isolates are the closest currently available phylogenetic relatives of USCα methanotrophs, which open the way for studies on biology and metabolic potential of this earlier uncultured group of bacteria.

Many novel members of the cosmopolitan genus *Methylocystis* have been characterized and the pool of good-quality genome sequences of these bacteria is now available for detailed studies on metabolic potential of these bacteria. As evidenced by cultivation-independent studies, *Methylocystis*-affiliated methanotrophs is one of the most abundant and functionally active groups of $CH_4$-oxidizers in various terrestrial environments.

A number of intriguing hypotheses were published during the last decade regarding the occurrence of methanotrophy in some uncultured groups of prokaryotes, such as the candidate phylum *Rokubacteria* and the lineage within the verrucomicrobial order *Methylacidiphilales* detected in acidic peatlands. The presence of methanotrophic capabilities in these bacteria was verified experimentally, by incubating the soil samples colonized by these bacteria with methane. No response to methane availability was detected for the *Rokubacteria* and for the *Methylacidiphilales*, while a clear increase in a relative abundance was observed for the conventional methanotrophs. The search for methane monooxygenase encoding genes in currently available *Rokubacteriales* metagenomes yielded negative results, although copper-containing monooxygenases were encoded by some members of this order. Similarly, no genome-encoded methanotrophic capabilities were revealed in metagenome-assembled genomes of *Methylacidiphilales*-affiliated bacteria. Therefore, not all claims for the existense of “novel” methanotroph groups could have been proven.

Thus, despite the impressive recent breakthroughs in methanotroph research, the currently assembled picture of methanotroph diversity in terrestrial habitats still has many gaps, which remain to be addressed in further studies.

# Ozone-driven spatial divergence of methane production in rice paddies

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**ABSTRACT**

Tropospheric ozone ($O_3$) pollution is intensifying globally under climate change, yet its effects on methane ($CH_4$) production in rice paddies—one of the largest anthropogenic $CH_4$ sources—remain poorly constrained. Here, using a free-air ozone enrichment (FACE- $O_3$) platform combined with rhizosphere and bulk-soil microcosm incubations, root metabolomics, and microbial ecological analyses, we reveal that elevated $O_3$ induces pronounced spatial heterogeneity in paddy soil methanogenesis. Exposure to 1.5× ambient $O_3$ significantly suppressed $CH_4$ production potential in rhizosphere soils (by 43-66%) but stimulated $CH_4$ production in bulk soils (by 21-158%), demonstrating that $O_3$ impacts on methane cycling are strongly compartmentalized rather than uniform.

Mechanistically, elevated $O_3$ triggered defensive metabolic reprogramming in rice roots, with purine metabolism and 2-oxocarboxylic acid metabolism acting as central regulatory pathways. This metabolic shift redirected carbon allocation from energy metabolism toward secondary defense compounds, reducing the supply of labile carbon to the rhizosphere. Consequently, dissolved organic carbon and microbial biomass carbon declined, constraining acetate-dependent methanogenesis and driving a pathway shift from mixed acetoclastic–hydrogenotrophic methanogenesis toward hydrogenotrophic dominance. In contrast, bulk soils were less directly influenced by root-derived substrates; instead, $O_3$-induced increases in pH and carbon availability favored hydrogenotrophic methanogens, resulting in a transition from acetoclastic dominance to a dual-pathway regime.

Microbial network analyses further revealed that elevated $O_3$ enhanced cooperation and efficiency within bulk-soil microbial communities, while rhizosphere networks exhibited functional degradation. Together, these findings demonstrate that $O_3$ pollution reshapes paddy $CH_4$ production through plant-mediated metabolic controls that differentially regulate rhizosphere and bulk-soil microbial processes. Our results highlight a previously underappreciated pathway by which air pollution interacts with plant physiology to modulate greenhouse gas emissions, with important implications for predicting agricultural methane feedbacks under future climate and air-quality scenarios.

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# Life under Limiting Methane
# Metabolic Flexibility, Hydrogen Use, and Starvation/Revival of Methylocystis spp.

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**ABSTRACT**

Aerobic methane-oxidizing bacteria (methanotrophs) play a key role in the global methane cycle by mitigating methane emissions from soils to the atmosphere. Among proteobacterial methanotrophs, alphaproteobacterial *Methylocystis* spp. are ubiquitous in wetland soils, where steep redox gradients and fluctuating gas diffusion expose cells to pronounced temporal and spatial variability in methane availability. While methane is the primary carbon and energy source for these organisms, wetlands frequently impose conditions of methane limitation or even complete methane absence. However, the cellular strategies that enable *Methylocystis* spp. to cope with these fundamentally different metabolic states remain poorly understood.

Using *Methylocystis* sp. strain SC2 as a model organism, we investigated physiological and proteomic responses to methane limitation and to complete methane deprivation. Growth experiments combined with proteomics revealed that strain SC2 can utilize hydrogen as an alternative energy source under methane-limited (6% $CH_4$) and oxygen-limited (3% $O_2$) conditions. Supplementation of the culture headspace with 2% $H_2$ resulted in a two-fold increase in maximum biomass yield compared to fully aerobic conditions without hydrogen addition. With decreasing $O_2/CH_4$ mixing ratios, methane utilization was progressively redirected from respiratory metabolism toward fermentation-associated pathways, irrespective of hydrogen availability. This metabolic shift was accompanied by strongly increased production of the membrane-bound Group 1d [NiFe]-hydrogenase in both short-term (19 h) and long-term (37 d) incubations, as well as the cytoplasmic Group 2b [NiFe]-hydrogenase. Group 1d [NiFe]-hydrogenase primarily oxidizes hydrogen at elevated concentrations during mixotrophic growth, with electrons transferred directly into the quinone pool, consistent with the availability of fermentation-derived $H_2$ in wetland soils.

In contrast, aerobic $CH_4$-free conditions induced a distinct hydrogenase expression pattern. The high-affinity, membrane-bound Group 1h [NiFe]-hydrogenase was strongly upregulated within 72 h and remained highly expressed during methane deprivation for up to one month, consistent with its role in scavenging trace or atmospheric hydrogen to sustain maintenance metabolism. Conversely, Group 1d, regulatory Group 2b, and Group 3b [NiFe]-hydrogenases were progressively downregulated, indicating selective repression of low-affinity hydrogenases under prolonged methane starvation. Beyond hydrogen metabolism, extensive proteome remodeling affected pathways involved in methane oxidation, $C_1$ metabolism, and polyhydroxybutyrate (PHB) turnover. While short-term methane starvation (3 h and 72 h) allowed full metabolic recovery upon methane re-addition, cultures starved for up to one month showed only partial recovery, indicating reduced cell viability under prolonged methane deprivation.

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# Temperature-Driven Virus-Host Interactions Regulating Methane Production in Paddy Fields

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**ABSTRACT**

Rice paddies are among the largest anthropogenic sources of methane, where soil temperature strongly regulates microbially mediated methane fluxes. While the roles of bacteria and archaea are well established, the contributions of viruses to these processes remains largely unexplored. Here, we combined metagenomic and metatranscriptomic analyses to determine virus-host interactions in paddy soils incubated under different temperatures. Viral sequences were detected in association with 37% of metagenome-assembled genomes (MAGs) and viral survival strategies shift under warming across different soil types, indicating widespread viral infection across both bacterial and archaeal lineages. Among bacterial hosts, members of Xanthobacteraceae and Burkholderiaceae showed increased transcription of fatty acid metabolism pathways. In archaea, Methanosarcinaceae, the dominant methanogenic family in paddy soils, were identified as the primary archaeal hosts of viral infection. Metatranscriptomic analysis revealed that under elevated temperatures, viruses affect both aceticlastic and methylotrophic methanogenesis pathways within Methanosarcinaceae. These findings highlight the significant role of viruses in regulating the methane cycle in paddy soils and demonstrate that temperature-dependent virus–host interactions can influence key methanogenic processes. Our results highlight an overlooked biological layer controlling methane emissions from rice paddies under climate-relevant temperature shifts.

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# Combined Effects of Elevated Ozone and Warming on Methanogenesis in Paddy Soil Across Depths

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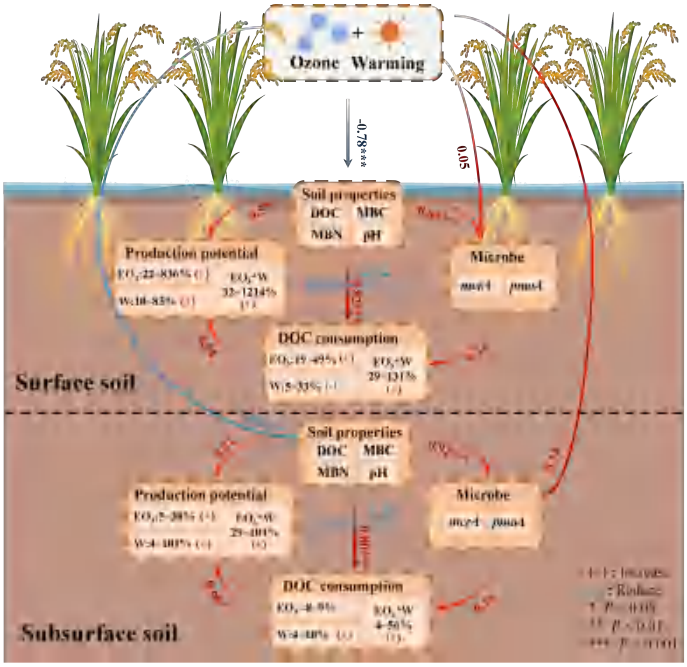
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## ABSTRACT

Elevated tropospheric ozone ($O_3$) concentrations and global warming represent critical environmental challenges; however, their combined impacts, particularly the indirect influences on methanogenesis in paddy soils, remain poorly understood. To clarify how methanogenesis responds to elevated $O_3$ (1.5× ambient) and warming (+2 °C), we sampled surface (0–10 cm) and subsurface (10–20 cm) soils throughout two rice seasons in an $O_3$-T-FACE (Free-Air Controlled Environment) platform and measured $CH_4$ production potential via anoxic incubation. The results showed that elevated $O_3$ levels increased the $CH_4$ production potential in surface soil by 22–836% compared to the control, whereas warming effects varied with the growth stage. Notably, their combined effects amplified $CH_4$ production potential in surface soils by 32–1214%, possibly owing to increases in initial dissolved organic carbon (DOC, 19–38%), microbial biomass carbon (MBC, 10–32%), methanogen abundance (28–97%), and DOC consumption during incubation (29–131%). In subsurface soils, elevated $O_3$ levels and warming individually enhanced $CH_4$ production potential by 5–38% and 4–101%, respectively, with their combined effect increasing it by 29–101%, linked to elevated methanogen abundance (4–290%) and DOC consumption (4–56%). Random forest and Partial Least Squares Path Modeling (PLS-PM) analyses collectively identified soil DOC concentration, DOC consumption, and $CH_4$ cycle-related microbial abundance as key determinants of methanogenesis across soil depths. These results underscore the dual control of abiotic and biotic factors on methanogenesis under future $O_3$ and warming, revealing a "surface sensitivity-subsurface buffering" pattern in paddy-ecosystem responses to elevated $O_3$ and warming.

**Key words** Methanogenesis, Elevated Ozone, Warming, Soil depth, Paddy Soil

**Graphical ABSTRACT**



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# Combined Effects of Elevated Ozone and Straw Return on Plant-Soil-Microbial Mechanisms Regulating Paddy Methane Emissions

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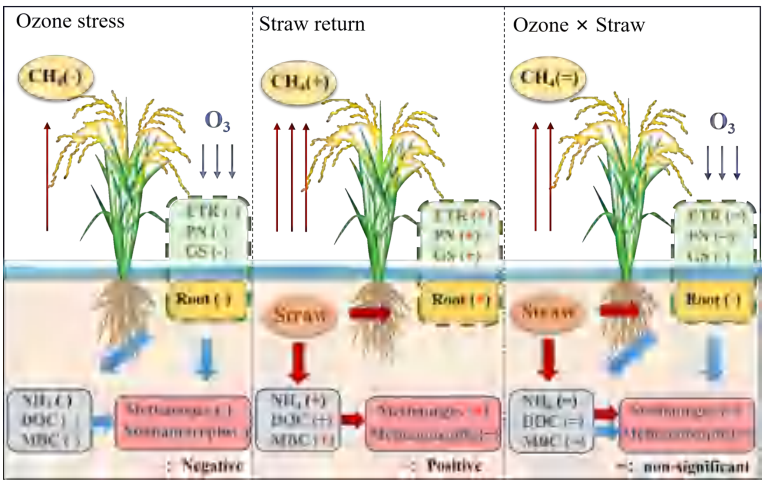
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## ABSTRACT

Against the background of climate change, this study focuses on the synergistic impacts of ozone ($O_3$) pollution and agricultural management practices on methane ($CH_4$) emissions from paddy fields. Based on an open-top chamber (OTC) platform, a split-plot experiment was systematically conducted to investigate the interactive effects of elevated $O_3$ concentration and straw return. Two $O_3$ concentration levels were established: non-filtered ambient air (NF) and targeted $O_3$ elevation of 60 ppb above ambient (NF60), which were combined with two straw treatments: no straw return (CK) and straw return (S). The rice cultivar 'HuiLiangyou' (*Oryza sativa* L.) was used as the experimental material. From the holistic perspective of "plant-soil-microbe", this study comprehensively analyzed rice photosynthetic physiological traits, biomass accumulation, and yield formation processes, as well as soil carbon and nitrogen physicochemical properties (dissolved organic carbon (DOC), ammonium nitrogen ($NH_4^+$-N), pH), $CH_4$ emission flux, and methane production potential (MPP) in paddy fields. Meanwhile, quantitative real-time polymerase chain reaction (qPCR) and high-throughput sequencing techniques were integrated to systematically decipher the abundance of the methane-functional gene (*mcrA*) and the structural characteristics of methanogenic microbial communities in paddy soil. The results demonstrated that $O_3$ and straw return synergistically regulated paddy $CH_4$ emissions through multi-level cascading effects. $O_3$ stress significantly suppressed rice photosynthesis, reduced root biomass, thereby decreasing the supply of rhizosphere carbon and nitrogen substrates, inhibiting the abundance of methanogens (e.g., *Methanobacterium*), and lowering $CH_4$ emission intensity. In contrast, straw return enhanced $CH_4$ production potential by supplementing soil carbon and nitrogen pools, promoting the enrichment of functional microbial communities, and upregulating the expression of functional genes. Notably, the interaction between $O_3$ and straw partially mitigated the negative effects of single $O_3$ stress on rice physiology, while attenuating the enhanced $CH_4$ emissions induced by sole straw application, achieving the synergistic effects of crop damage mitigation and $CH_4$ emission reduction. Partial least squares path modeling (PLS-PM) analysis further clarified that $O_3$ indirectly inhibited $CH_4$ emissions primarily through the "plant physiology-rhizosphere microorganisms" pathway, whereas straw return promoted $CH_4$ production via the "soil carbon and nitrogen-microbial communities" pathway. This study systematically uncovers the multi-path regulatory mechanisms of $O_3$ pollution and straw return on $CH_4$ emissions in paddy ecosystems, providing a scientific basis for $CH_4$ emission reduction and sustainable agricultural management in paddy fields under future climate change scenarios.

**Keywords:** Methane Emissions, Elevated Ozone, Straw Return, Plant-Soil-Microbial Interactions, Paddy

## GRAPHICAL ABSTRACT



# Microbial-Driven Humification of Sugarcane Leaf Residues in Lateritic Soils

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**ABSTRACT**

Humus is the main body of soil organic matter and plays an important role in maintaining the stability of soil carbon pools. The formation of soil humus, mediated by the microbial decomposition of plant litter, is pivotal for terrestrial carbon sequestration and climate regulation. In Southern China, lateritic ecosystems face severe degradation characterized by acidification, nutrient depletion, and biodiversity loss. However, sugarcane production in this region generates tens of millions of tons of sugarcane leaf residue annually, conventional disposal methods such as burning fail to utilize this biomass effectively, hindering soil carbon replenishment. Transforming this agricultural waste into stable soil organic carbon represents a critical challenge for restoring lateritic ecosystem functions. Herein, we investigated the humification process of sugarcane leaves in lateritic soil driven by microbiota from various land-use types. We enriched cultivable bacteria and fungi to construct distinct microbial inocula and applied them to sugarcane leaf-amended lateritic soil. High-throughput sequencing and physicochemical analyses were used to track microbiome dynamics and nutrient turnover. The results indicated that the addition of microbiota from vegetable field and forest soil resulted in the highest rate of humus formation compared to controls. Specifically, the abundance of *Cellulomonas*, *Roseomonas*, *Solitalea*, *Hydrogenophaga*, and *Ruminiclostridium* was significantly correlated with the increase in soil organic carbon, humic substances, available phosphorous and available potassium. These findings clarify the mechanism of microbial-mediated humification and offer a practical bio-strategy for restoring degraded lateritic ecosystems and achieving carbon sequestration targets.

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# Vertical profiles of community and activity of methanotrophs in large lake and reservoir of Southwest China

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## ABSTRACT

Microbial methane oxidation plays a significant role in regulating methane emissions from lakes and reservoirs. However, the differences in methane oxidation activity and methanotrophic community between lakes and reservoirs remain inadequately characterized. In this study, sediment and water samples were collected from the large shallow lake (Dianchi) and deep reservoirs (Dongfeng and Hongjiadu) located in karst area, Southwest China. The results indicated that the rates of aerobic oxidation of methane (AeOM) in lake sediment ranged from 7.1 to 27.7 $\mu g \cdot g^{-1} \cdot d^{-1}$, which was higher than that in reservoirs sediment (1.92 to 11.56 $\mu g \cdot g^{-1} \cdot d^{-1}$). Similarly, the average AeOM in the water column of lake (104.7 $\mu g \cdot L^{-1} \cdot d^{-1}$) was much higher than that of reservoirs (46 $\mu g \cdot L^{-1} \cdot d^{-1}$). The content of sediment organic carbon and dissolved inorganic carbon were important factors that influenced the rates of AeOM in sediment and water column, respectively. 16S rRNA genes sequencing revealed a higher relative abundance of methanotrophs in lake sediments compared to reservoir sediments. The dominant methanotrophic taxa in lake was *Methylococcaceae* (type Ib), while *Methylomonadaceae* (type Ia) was predominant in reservoirs. Meanwhile, anaerobic methane-oxidizing microorganisms *Candidatus Methylomirabilis* and *Candidatus Methanoperedens* were also abundant in sediments of reservoirs. However, metatranscriptomic analysis revealed that the type I methanotrophs, especially *Methylobacter*, was most active in the sediment of both lake and reservoir. Water depth and conductivity could be the key controlling factors of the structures of methanotrophic communities in sediment and water column, respectively. Metagenome-assembled genomes suggested that type I methanotrophs exhibited greater motility, as evidenced by a higher number of flagellar assembly genes, while type II methanotrophs demonstrated advantages in metabolic processes such as carbon, phosphorus, and methane metabolism.

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# Elevational patterns and temperature sensitivity of soil methane oxidation in southeastern Tibetan forests

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**ABSTRACT**

Methane ($CH_4$) is a potent greenhouse gas, yet substantial uncertainties remain regarding how the temperature sensitivity of soil methane oxidation varies along elevational gradients and the extent to which microbial regulation and long-term thermal adaptation shape these patterns. Here, we investigated soil methane oxidation across 28 forest sites in southeastern Tibet spanning a continuous elevational gradient from 1,404 to 4,513 m. In situ methane flux measurements revealed a pronounced unimodal elevational pattern, with methane uptake increasing with elevation to a maximum at approximately 3,113 m before declining at higher elevations. Consistent with field observations, laboratory incubations conducted at 0, 10, and 20 °C showed peak methane oxidation rates at intermediate elevations (~3,113 m). The temperature sensitivity ($Q_{10}$) of methane oxidation declined with increasing incubation temperature, with higher $Q_{10}$ values at 0–10 °C (mean = 1.41) than at 10–20 °C (mean = 1.13). Moreover, $Q_{10}$ showed a weak, non-significant positive trend with elevation at low incubation temperatures, but a weak, non-significant negative trend at higher temperatures, suggesting contrasting temperature responses across the elevational gradient. Together, these results demonstrate temperature-dependent regulation of soil methane oxidation in cold-region forests and highlight the limitations of representing methane oxidation temperature responses using a single $Q_{10}$ value. Our findings underscore the importance of considering microbial thermal adaptation when predicting future soil methane sink strength under climate warming.

**Keywords:**Methane oxidation; Temperature sensitivity; Elevational gradient

**Acknowledgments**

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# Functional Diversity and Interactions of CO-utilizing Microbial Communities

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**ABSTRACT**

Microbial transformation of one-carbon (C1) gases plays a fundamental role in carbon cycling across diverse anoxic environments. We investigate the physiology, metabolic diversity, and interactions of microorganisms capable of utilizing CO and $CO_2/H_2$ as carbon and energy sources under anoxic conditions, providing mechanistic insight into C1 metabolic processes.

In anaerobic enrichment cultures, CO conversion is typically dominated by methanogenesis, reflecting the strong thermodynamic coupling between CO oxidation and methane formation. However, at elevated CO concentrations, methanogenic activity is inhibited, leading to a metabolic shift in which acetate becomes the primary product of CO conversion via acetogenic carboxydotrophs. Under conditions where methanogenesis is suppressed, alternative metabolic routes can emerge within the community, enabling further transformation of acetogenic products. In this context, we have shown that enriched and defined microbial communities can redirect carbon and electron fluxes from CO toward the formation of elongated even- and odd-chain carboxylic acids and alcohols, driven by metabolic interactions between acetogens, propionigenic bacteria, and chain-elongating bacteria.

Genomic surveys across diverse anoxic environments consistently reveal genes encoding carbon monoxide dehydrogenases (CODHs), indicating that the potential for CO utilization is widespread, whereas the majority of carboxydotrophic microorganisms remain uncultivated. To address this gap, we focus on the isolation of CO-utilizing microbes from constrasting environments, using cultivation strategies adapted to different physicochemical constraints. Our work has recovered carboxydotrophs from anaerobic sludges, volcanic and geothermal sediments, and high-salinity environments, including novel thermophilic members of the Bacillota lineage, the new genus *Thermobium azorense*, and hydrogenogenic CO utilizers affiliated with *Thermincola* and *Carboxydocella*. Recognizing that conventional enrichments may bias against slow-growing or CO-sensitive taxa, we are further developing refined isolation strategies to recover underrepresented carboxydotrophic lineages, advancing our ability to link genomic potential with physiological function across taxonomic and ecological space.

# Culturing the Uncultured Anaerobes from the Perspective of Microbial Growth Curves

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**ABSTRACT**

Anaerobic microorganisms, e.g methanogenes, inhabit diverse anoxic environments and play a fundamental role in global biogeochemical cycles. Recent advances in DNA sequencing have revealed a striking gap between the vast microbial diversity found in anoxic environments and the small number of anaerobes – fewer than 0.1% of the estimated millions of anaerobic species in nature have been cultivated. This challenge reflects the “great plate count anomaly”, where most microorganisms observed in nature fail to grow in laboratory conditions. Overcoming these limitations requires a shift in cultivation strategies. Here, I will introduce a growth-curve-guided strategy that uses real-time monitoring of microbial growth (primarily at the species level) to inform approaches that leverage relative growth advantages and improve the recovery of target microorganisms. By prioritizing growth performance over abundance and selectively removing non-target microbes, this approach offers a more predictable and adaptable framework for isolating methanogens from complex communities.

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# The overlooked methanogenic N2-fixation revealed during rice straw incorporation by metatranscriptomics

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**ABSTRACT**

For paddy soils undergoing straw returning, microbial-driven $N_2$ fixation is an important natural pathway for soil nitrogen enhancement. However, the types and activities of microorganisms, especially $N_2$-fixing microorganisms, during the anaerobic degradation of rice straw in paddy soil are still poorly understood. Herein, we use $^{15}N$ isotope method and a range of molecular methods including metatranscriptome sequencing to study how rice straw degradation affects microbial $N_2$ fixation. Using untreated control (CK), Straw, and Straw+N (Urea) treated soils it was found that the degradation of rice straw only vigorously promoted $N_2$ fixation activity of soil microorganisms in treatment Straw. Firmicutes was the dominant phylum that degraded rice straw and was also a main driver for $N_2$ fixation. Proteobacteria and methanogens of the Euryarchaeota phylum were another two major $N_2$-fixing taxa during anaerobic degradation of rice straw. The metatranscriptomic approach demonstrated the non-negligible role of methanogens in $N_2$ fixation although their proportion in total microorganisms was extremely low. Urea addition not only terminated the $N_2$ fixation activity of microorganisms in paddy soil but also changed the composition of control (CK), Straw, and Straw+N (Urea) treatment soils the methanogenic community and reduced methane production. These results revealed a panoramic view (global insight) of active diazotrophs during the early anaerobic degradation of rice straw in paddy soil.

**Keywords:** nitrogen fixation; metatranscriptome; diazotrophs; rice straw; paddy soil

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# Mechanistic insights of manganese-resistant bacteria in enhancing heavy metal phytoremediation by Koelreuteria paniculata

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## ABSTRACT

Manganese (Mn) tailings pollution poses a severe threat to soil quality and human health. Phytoremediation is effective for Mn tailings pollution, but the mechanisms of plant-microbe interactions in this process need further investigation. By inoculating *Koelreuteria paniculata* roots with *Priestia megaterium* (PM), we assessed changes in soil properties, plant physiology and heavy-metal uptake, then mined the root transcriptome for genes linked to Mn-tailings tolerance. Soil organic carbon, total nitrogen, total phosphorus, available nitrogen, available phosphorus, microbial biomass carbon, microbial biomass nitrogen content, soil β-glucosidase, acid phosphatase, and leucine aminopeptidase activities were increased by inoculation with the strain PM. Under 100% Mn tailings, plant biomass, net photosynthetic rate, stomatal conductance, transpiration rate, total chlorophyll content, and the activities of superoxide dismutase, peroxidase, and catalase were significantly increased after PM inoculation, with respective increases of 17.6%, 32.8%, 35.9%, 216.9%, 59.5%, 116.2%, 179.2%, and 279.4%. Meanwhile, after inoculation with strain PM, the malondialdehyde content of *K. paniculata* decreased significantly. Inoculation with the strain PM increased the percentages of iron (Fe)/ Mn oxide-bound and organic-bound Mn and copper (Cu) in the soil, as well as the accumulation and bioconcentration factors of Mn and Cu. After inoculation with strain PM, the key genes involved in antioxidant response (*UGT72E*, *IF7MAT*, *FG3*, *WRKY25* and *WRKY52*), plant photosynthesis genes (*IDO*, *crtZ*) and growth regulation genes (*ARR-A*) were significantly up-regulated. These findings highlight key genes involved in plant growth and antioxidant responses, offering insights for future phytoremediation strategies.

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# A "naturally dominant" chemo-denitrification pathway drives $N_2O$ emissions in Tibetan glacier retreat zones

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**ABSTRACT**

Glacier retreat on the Tibetan Plateau, driven by rapid warming, is exposing vast areas of iron-rich parent material, yet the impact of this process on nitrous oxide (N2O) emissions remains unknown. Here we show that chemo-denitrification, the abiotic reduction of nitrite by ferrous iron (Fe(II)), dominates $N_2O$ production in Tibetan glacier forelands. In proglacial wetlands and meadows, chemo-denitrification contributed 50–69% of total $N_2O$ production from denitrification, and in three additional glacier retreat zones (Jiali County, Mount Everest, Cho Oyu) its contribution exceeded 60%. Unlike tropical peatlands where chemo-denitrification outcompetes an active microbial community, here denitrification functional genes and microbial activity was extremely low. Consequently, $N_2O$ is produced abiotically through Fe (II) driven nitrite reduction without subsequent microbial consumption a "naturally dominant" mode distinct from the "competitively dominant" mode observed elsewhere. With glaciers on the plateau shrinking by 0.5% per year, the expanding Fe (II)-rich forelands are becoming an overlooked source of abiotic $N_2O$. Our findings challenge the paradigm that denitrification is primarily a biological process and call for inclusion of iron-driven chemo-denitrification in Earth system models to accurately project high-alpine greenhouse gas emissions under continued warming.

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# Understanding methane emission dynamics in temperate rice fields through systematic review and statistical modeling

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## ABSTRACT

Rice cultivation contributes to methane (CH4) emissions to the atmosphere and represents approximately 10% of total agricultural emissions. While Asia dominates global rice production, rice paddies in temperate regions such as Europe and North America also contribute significantly to GHG budgets. Accurate estimation of greenhouse gas emissions from rice paddies is increasingly crucial for evaluating agricultural management strategies aimed at mitigating global warming, as well as for reporting emission inventories at regional and national scales. While emission models are well-established for tropical regions, their performance in temperate zones such as Europe and North America remains limited and poorly validated leading tohigh uncertainty. This study addresses this gap by focusing on rice-producing regions in temperate regions including Europe and the USA, which are characterized by high mechanization, artificial irrigation, and comparable agronomic practices.

A systematic literature review was performed to identify field-based studies measuring $CH_4$ emissions using non-steady state closed chamber technique in temperate rice systems. The review yielded 40 eligible publications, supplemented by proprietary data from UpToFarm Srl, a spin-off company of the University of Torino, resulting in a dataset of 223 statistical units. For each unit, $CH_4$ emission factors were calculated as the average daily emission rate (kg $CH_4$ $ha^{-1}$ $d^{-1}$) over the cropping season. Explanatory variables describing water and residue management, soil and climate characteristics, and agronomic inputs were compiled.

Generalized Linear Mixed Models (GLMMs) and Generalized Additive Mixed Models (GAMMs) were used to explore the relationships between $CH_4$ emissions and environmental and management factors. GAMMs performed better than GLMMs according to Akaike Criterion (AIC). The most accurate model identified soil pH, water management during cropping cycle and seeding, nitrogen and carbon inputs, and soil sand content as significant predictors. Non-linear effects were detected for pH, nitrogen inputs, and sand fraction, with country and year included as significant random effects. These Our findings emphasize the importance of local agronomic and environmental conditions in determining $CH_4$ emissions in temperate rice systems and highlight the need for region-specific approaches to improve emission estimates. Including data from Europe and the USA not only strengthens global model reliability but is essential to inform sustainable policy design in these under-represented but high potential emission regions.

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# Carbon Dioxide Emissions from Soil Can Serve as a Sustainable Characteristic of the Forest-Steppe Biome

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**ABSTRACT**

This study focused on evaluating the influence of qualitative (categorical, nominal) factors on $CO_2$ emissions from soil, that is, soil respiration (SR), at a single biome scale. The factors were as follows:

- "Region" − represented by four regions (Chuvashia, Ryazan, Tula and Kursk regions) and characterizing the geographical location within the European part of the forest-steppe biome. It was a generalized indicator of local conditions, including soil type and economic activity of farms;
- "Year" − corresponded to five years of measurements (2020–2024). The factor should be interpreted as a cumulative characteristic of weather and the state of soil and vegetation cover;
- "Ecosystem" − the seven types of ecosystems were categorized as either agricultural (croplands, pastures and hayfields) or natural (grasslands and forests), as well as livestock facilities (stockyards and compost piles).
- "Crop" − an additional factor addressed with the arable soil group. We analyzed the influence of crops grown during the measurement period (winter and spring wheat, barley, oats, corn, soybeans, sunflowers and fallow).

SR measurements were performed using closed chamber technique in different ecosystems over a short period at the height of the growing seasons. Multivariate non-parametric analysis (three-way PERMANOVA and ANOSIM) was employed.

The results showed that the geographical location of a particular site (region) within the forest-steppe biome did not affect the rate of soil $CO_2$ efflux, whereas the type of land use (ecosystem type) and current environmental conditions were the key controls. SR was found to be similar in perennial plant communities (pastures, hayfields, grasslands, forests), lower in croplands, and an order of magnitude higher in livestock facilities. Consequently, these results suggested that distant sites may not reveal spatial variability in SR. The similarity of the SR in different regions of the forest-steppe biome was consistent with the observation that soil organic carbon contents were often comparable between different ecosystems. However, this indicator was characterized by high variability, with a tendency to increase from north to south and to decrease in arable soils. Overall, the average SR rate varied slightly spatially and could therefore be considered a sustainable characteristic of the biome, alongside climate, soil type, and vegetation cover. For the forest-steppe biome (excluding livestock facilities), the average SR rate was 0.227 g C·m-2·h-1 (mean), 0.239 g C·m-2·h-1 (weighted mean), 0.167 g C·m-2·h-1 (median) in the middle of the growing season.

**Acknowledgments**

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# Agricultural Management and Soil Leakiness: Drivers of Methane Oxidation and Nitrification

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**ABSTRACT**

Upland soils play a crucial role in climate regulation by acting as both sinks and sources of greenhouse gas (GHG). Compared to natural upland ecosystems, agricultural soils often exhibit higher "leakiness" owing to intensive management practices such as high nitrogen inputs and frequent soil disturbances, which weaken methane ($CH_4$) sink capacity while enhancing nitrous oxide ($N_2O$) emissions. Although the effects of individual agricultural practices on soil methane and N-cycling dynamics have been widely examined, the combined and interacting impacts of multiple co-occurring practices remain poorly understood. This study investigates how interacting agricultural management practices jointly influence soil methane oxidation potential, nitrification potential, and GHG fluxes through biotic and abiotic pathways. We analyzed 207 soil samples collected from agricultural grassland and arable fields all over the Netherlands, representing contrasting management intensities and soil types. By integrating management data, soil physicochemical properties, and microbial community profiles, we identify likely drivers of $CH_4$ oxidation and nitrification processes. Methanotrophic (MOB) and ammonia-oxidizing communities, comprising ammonia-oxidizing bacteria (AOB), archaea (AOA), and complete ammonia oxidizers (comammox), are profiled to reveal their functional and ecological responses to management intensity. The combined analyses aim to construct a predictive framework linking management practices to soil "leakiness," defined by the balance between sink and source function. Our findings are expected to improve mechanistic understanding of how integrated agricultural management modulates microbial processes driving GHG dynamics, and to provide insights for designing management strategies that enhance soil functioning and climate change mitigation.

**Acknowledgments**

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# Soil greenhouse gas emissions under different land uses across Europe

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**ABSTRACT**

Changes in land use have been identified as a main cause of carbon (C) and nitrogen (N) changes in soils across different regions of the world. In Europe, where there is a wide variety of climates and soil types, the role of land use and land use change on C and N dynamics may be complex showing different patterns depending not only on the specific land use and geographical region but also on the intensity of the land use. Furthermore, the effects on soil C and N can influence the production, transport, and emission of soil gases.

In this context, the aim of this study was (i) to assess how land use affects soil greenhouse gas (GHG) emissions in different European regions, and (ii) to determine whether land use intensity influences the emission of soil gases. Sampling areas were located in five European biogeographical regions and countries: Mediterranean (Spain), Atlantic (Spain), Alpine (Switzerland), Continental (Germany) and Boreal (Latvia). Five different land use types were selected in each biogeographical region. The selection of land uses in each region varied according to the most common land uses: agricultural (all five regions), seminatural (all five regions), forest (Alpine, Boreal and Continental), industrial (Alpine and Mediterranean), mining (Atlantic, Boreal, Mediterranean and Continental), urban (Atlantic, Mediterranean and Continental), and wetland (Alpine, Atlantic and Boreal). Within each land use and region, three intensity levels were selected ranging from the most to the least degraded condition.

In spring 2024, soil sampling was conducted in each biogeographical region. Ten composite soil samples (each composed from 5 points) were collected from the 0-20 cm layer for each combination of land use and intensity, resulting in a total of 750 soil samples. Air-dried soil samples (<4 mm) were pre-incubated for 48 h under uniform soil moisture and temperature conditions and subsequently incubated for 72 h in airtight containers. During the incubation period, multiple air samples were collected to determine the concentration of carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$).

Considering all biogeographical regions, land uses showed significant differences in cumulative $CO_2$ and $N_2O$ emissions. Seminatural and wetland uses showed higher cumulative soil $CO_2$ emissions than urban and industrial uses, while agricultural use showed greater $N_2O$ emissions than seminatural, urban, mining and industrial uses. Regarding biogeographical regions, the Alpine and Boreal regions showed the highest cumulative $CO_2$ and $N_2O$ emissions, respectively.

This study highlights the key role of land use and land use change in soil C and N dynamics, and consequently in the production and emission of $CO_2$ and $N_2O$ in European soils. Therefore, land use planning is crucial for reducing soil greenhouse gas emissions and achieving carbon neutrality targets established by the European Commission for the coming decades.

**Acknowledgments**

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# Greenhouse Gas Emissions from Soils and Ways to Reduce Them

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**ABSTRACT**

Greenhouse gas emissions from soils account for 15% of the global increase in climate warming (radiative forcing) experienced today. Soil emissions of the three main anthropogenic greenhouse gases are 0.1 Pg C $yr^{-1}$ of carbon dioxide, 3.7 Tg $N_2O$-N $yr^{-1}$ of nitrous oxide and 30 Tg $CH_4$ $yr^{-1}$ of methane (Figure 1). Various aspects of human activity, especially land-use and management, contribute to these emissions.

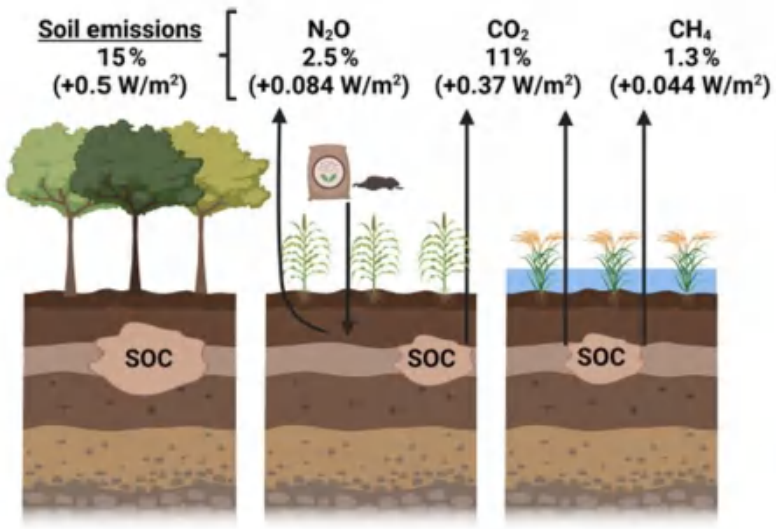



**Figure 1.** Anthropogenic emissions of greenhouse gases (carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$)) from soil, and their contribution (15 %, +0.5 $Wm^{-2}$), to the overall increase in warming (radiative forcing) due to well-mixed greenhouse gases (+3.32 $Wm^{-2}$) (Kopittke et al., 2024)

In this presentation I will draw on 30 years of research into these topics (Smith et al., 2012) to highlight what we know about soil emissions of greenhouse gases and their responses to land use and land management, what we still do not know, and what we can do to reduce net greenhouse gas emissions from soils (Smith et al, 2008).

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# Recent stabilization of agricultural non-$CO_2$ greenhouse gas emissions in China

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## ABSTRACT

Agriculture emerges as a prominent contributor to $CH_4$ and $N_2O$ emissions in China. However, estimates of these two non-$CO_2$ greenhouse gases (GHGs) remain poorly constrained, hindering a precise understanding of their spatiotemporal dynamics and the development of effective mitigation strategies. Here, we established a consistent estimation framework that integrates emission-factor approach, data-driven models and process-based biogeochemical models, to identify the magnitudes, spatial variations, and long-term trends of agricultural non-$CO_2$ GHG emissions in China's mainland from 1980 to 2023. Over the study period, the average total agricultural non-$CO_2$ GHG emissions amounted to 722.5 ± 102.3 Tg $CO_2$-eq $yr^{-1}$, with livestock $CH_4$, cropland $CH_4$, cropland $N_2O$ and livestock $N_2O$ contributing 41% (297.4 ± 64.3 Tg $CO_2$-eq $yr^{-1}$), 31% (225.0 ± 69.6 Tg $CO_2$-eq $yr^{-1}$), 18% (130.6 ± 9.4 Tg $CO_2$-eq $yr^{-1}$) and 10% (69.4 ± 20.2 Tg $CO_2$-eq $yr^{-1}$), respectively. Approximately 70% of these emissions were concentrated in the eastern region beyond the Hu Line, with emission hotspots identified in South-central China, East China, and the Sichuan Basin. Our analysis revealed three distinct temporal stages of total emissions during the study period: rapid growth (1980–late 1990s), slow growth (late 1990s–middle 2010s), and a stabilization stage (since the middle 2010s). These stages reflect the evolving trajectory of agriculture in China, from the expansion of agricultural yields, to the transformation of agricultural practices, and ultimately the pursuit of sustainable development. However, the temporal trajectory of emissions varied significantly across different regions, highlighting divergent levels of agricultural development. This study presents a comprehensive, gridded, and consistent estimate of agricultural non-$CO_2$ GHG emissions in China, offering valuable insights for policymakers to develop tailored strategies that adapt to local conditions, enabling effective emission reduction measures.

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# Rainfall-induced hot moments of $N_2O$ emissions in sandy agricultural soils managed with winter cover crops

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**ABSTRACT**

Intensive fertilization in sandy Coastal Plain soils often results in substantial nitrogen (N) loss due to the soils' poor water- and nutrient-holding capacity and rapid leaching. Winter cover crops are therefore incorporated to retain soil residual N and reduce runoff and soil erosion. However, their effects are complicated by the diversity of species, varied management practices, and environmental conditions. A field study was conducted in a corn-cotton system at the Pee Dee Research and Education Center (Florence, South Carolina, U.S.A.), in which four cover crop treatments were tested (cereal rye, hairy vetch, rye-vetch mixture, and a fallow control). High-frequency gas sampling was employed to quantify "hot moments" of gaseous emissions, including nitrous oxide ($N_2O$) and ammonia ($NH_3$), with manual and automated chambers. Lysimeters were installed to measure liquid N losses, while soil samples were simultaneously collected to monitor N pools (i.e., extractable NH4, NO3, dissolved organic N, and microbial biomass). Preliminary data suggested that "hot moments" of $N_2O$ emissions did not occur after fertilization but were triggered by rainfall following high soil moisture content and water-filled pore space (WFPS). The magnitude varied with cover crops. The rye-vetch mixture produced the highest $N_2O$ fluxes, concurrent with the highest WFPS and $NO_3$ availability, favorable for denitrification. A similar "hot moment" of N leaching was also observed after rainfall, with the most significant loss occurring in the fallow controls, highlighting the potential of cover crops to reduce N leaching loss, most notably with cereal rye. Likewise, $NH_3$ volatilization was the highest and sustained in control plots following fertilization. These findings demonstrate that rainfall is the primary driver of gaseous N loss in the tested sandy soils, especially in soils where external organic C (rye residues) and N (vetch) were added together. However, these emissions can be effectively mitigated by targeted cover crop selection.

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# Global Response and Mechanism of Methane Cycling in Wetlands Under Elevated Atmospheric $CO_2$ and Warming

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## ABSTRACT

Wetland is one of the most significant sources of methane ($CH_4$). Although global warming and elevated atmospheric carbon dioxide concentrations ($eCO_2$) are expected to affect the $CH_4$ cycle, the response of $CH_4$ emission in natural wetland and paddy has been observed to be inconsistent. This variation is likely due to the complex interactions among soil, plant, and microbial processes that regulate $CH_4$ dynamics, leaving the underlying mechanisms across global studies unknown. Here, we conducted a meta-analysis to elucidate the effects of warming, $eCO_2$, and their co-effects on $CH_4$ cycling in wetland. Our results demonstrate that $eCO_2$ significantly increased $CH_4$ emission in paddy (18.57%) but had no significant effect on that in natural wetland, attributed to $eCO_2$-induced increase in belowground biomass and methane production potential in paddy. Conversely, warming promoted $CH_4$ emission in natural wetland (26.71%) but had no substantial impact on $CH_4$ in paddy. This difference is due to the lower mean annual temperature in natural wetland compared with paddy, where warming promotes plant growth and methanogen activity. Notably, the combined effects of $eCO_2$ and warming on paddy $CH_4$ emission were markedly greater than their individual effects, with a synergistic increase of 44.63%. Furthermore, the impact of $eCO_2$ on $CH_4$ emitted by natural wetland was enhanced with time, likely due to different extent of plant-induced priming effect and progressive nitrogen limitation, while $CH_4$ emissions from paddies declined greatly with time. Our findings emphasize the pivotal role of wetlands in the global methane cycle and highlight the complex responses of $CH_4$ emissions to climate changes.

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# $CO_2$ fixation by soil algae in agricultural lands

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## ABSTRACT

In the soil carbon cycle, microorganisms are primarily decomposers and converters of plant-derived organic matter, and the significance of $CO_2$ fixation by soil microorganisms has not been fully considered. In this study, we evaluated $CO_2$ fixation by soil algae in agricultural lands and analyzed its spatio-temporal variation and its relationship with environmental factors.

Soil $CO_2$ fluxes were measured under dark and light conditions (800 μmol $m^{-2}$ $s^{-1}$) in rice paddies and upland fields at the Togo Field, Field Science Center, Graduate School of Bioagricultural Sciences, Nagoya University, using an LED-equipped chamber placed on the soil, avoiding vegetation. Among 347 measurements, 263 (75%) showed lower $CO_2$ flux under light than under dark conditions, suggesting that a part of the $CO_2$ released by soil respiration was reabsorbed at the soil surface by algal photosynthesis at many sites. The rate of $CO_2$ uptake (net primary production, NPP) by soil algae accounted for 0–100% (median 24%) of soil respiration (D flux), with additional atmospheric $CO_2$ uptake detected for some cases. NPP positively correlated with D flux, temperature (soil and air), and moisture (soil water, humidity, precipitation).

Light-induced $CO_2$ uptake (200 μmol $m^{-2}$ $s^{-1}$) also occurred in indoor incubations (25 °C) using 0–5 cm soil cores (n = 68) from multiple sites. NPP in these cores correlated positively with D flux, soil moisture, and chlorophyll a; in paddy soils, it also correlated with water-extractable $NH_4^+$-N. Random Forest regression of field and indoor data identified D flux and soil moisture as the most important predictors of NPP.

D flux and NPP were measured over time in cores prepared under wet and dry conditions, respectively, with water loss during incubation replenished as needed. Both paddy and field soil cores under wet conditions (33% and 20% of water content, respectively) showed NPP equal to or higher than D flux throughout the period. Under dry conditions, NPP remained equal to or higher than that on the first day of incubation until moisture content dropped to 20% in paddy soil cores and 12% in field soil cores, after which NPP decreased further when moisture content dropped to 7.4%. After rewetting, NPP increased within a few hours in both paddy and field cores, reaching a maximum in 4 days in paddy and 2 days in field cores. NPP at this point was equivalent to that before soil drying proceeded. When soil moisture content decreased again, NPP decreased, as it did during the initial drying conditions.

These results demonstrate that photosynthesis by soil algae contributes significantly to the carbon balance of agricultural soils. Algal photosynthetic activity closely tracks soil respiration and moisture levels, tolerates moderate desiccation, and recovers rapidly after rewetting, indicating adaptive responses to fluctuating soil water conditions.

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# Effect of no-tillage based cover crop management on greenhouse gas emissions, and greenhouse gas balance in organic soybean field in Hokkaido, Japan

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## ABSTRACT

Cover crops and no tillage are recognized for mitigating greenhouse gas (GHG) emissions and enhancing carbon storage, yet their effects on the net GHG balance remain uncertain. This study evaluated the impacts of tillage and cover crop management without chemical fertilizers on greenhouse gas budget (GHGB), and GHG intensity (GHGI) in Hokkaido, Japan. Study period was from September 2023 to September 2024. Four treatments were established: conventional (C), tillage without fertilizers (TNF), no tillage without fertilizers (NTNF) and no tillage without fertilizer with rye cover (NTNFR). Bark manure (3.75 t $ha^{-1}$) was applied to all plots on September 28, 2023, and inorganic fertilizer (15:110:80 $N:P_2O_5:K_2O$) was used only in C. Rye used as green manure in NTNFR was terminated in soil surface before soybean sowing. Emissions of $CO_2$ from heterotrophic respiration (Rh) from bare plot, $CH_4$, and $N_2O$ were measured throughout experiment using static closed chamber. GHGB was calculated as the sum of global warming potentials (GWP) of Rh, $CH_4$, and $N_2O$ emissions, plus carbon output from soybean grain and weed, minus carbon inputs from net primary production (NPP) of weed, soybean, rye, and inputs from seed and bark manure.

Soybean yield did not significantly differ among treatments. Annual GWP was not significantly different, though values tended to be higher in TNF (19.2 Mg $CO_2$-eq $ha^{-1}$) and lower in C (14.6 Mg $CO_2$-eq $ha^{-1}$), likely due to higher Rh in TNF (5.10 Mg C $ha^{-1}$) versus C (83 Mg C $ha^{-1}$). Higher Rh in TNF compared to C likely attributed to significant positive correlation with water content in both TNF and C which may have accelerated the Rh in higher soil water condition. Nutrient limitations in the TNF may have reduced plant biomass, in turn reducing transpiration demand. This conserved soil moisture compared to C, created more favorable conditions for microbial activity, stimulating higher Rh in TNF. Although GHGB did not differ significantly, values were numerically higher in TNF (12.6 Mg $CO_2$-eq $ha^{-1}$), followed by NTNF (11.2 Mg $CO_2$-eq $ha^{-1}$), NTNFR (8.97 Mg $CO_2$-eq $ha^{-1}$), and C (8.45 Mg $CO_2$-eq $ha^{-1}$). Lower annual Rh in C contributed to lower GHGB, while higher $GWP_{CO_2}$ in TNF likely contributed to greater GHGB. GHGB tended to be lower in the NTNFR, possibly due to reduced NPP of soybean associated to N immobilization by high C:N rye, which suppressed soybean growth. Reduced soil disturbance under no tillage, with high C:N rye mulch, might slow organic matter decomposition, contributing to lower GHGB. Results suggest that integrating cover crop, such as rye, under no tillage management is essential for reducing GHGB. However, GHGI tended to be lower in C and higher in NTNF, suggesting lower and higher yield efficiency in each management, respectively. To mitigate GHG emissions in these systems, adopting slow decomposing organic amendments (biochar), integrating compost or manure, and optimizing cover crops or weed management is recommended.

# Coupling expression of nitrifying and denitrifying genes induce high $N_2O$ emissions in strong ammonia oxidizing soils

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## ABSTRACT

Ammonia oxidation contributes to nitrous oxide ($N_2O$) emissions both by direct production and by fueling denitrification. Urea or ammonia-based fertilizers account for about 70% of annual nitrogen fertilizer use globally. Soil ammonia oxidation and its coupled processes are therefore significant contributors to $N_2O$ emissions. However, the mechanism of microbial activities underpinned the coupled processes leading to $N_2O$ production remains unclear. Here, by using a robotized incubation and gas monitoring system (Robot) and meta-genomic and transcriptomic technique, we studied the dynamic and relationship of $O_2$ consumption, gas production ($N_2O$, nitric oxide NO, nitrogen $N_2$), gene expression of nitrification and denitrification and composition of active microorganisms in an alkaline agricultural soil of Northern China, which has a strong ammonia oxidizing rate and is a global $N_2O$ hotspot. The results showed that, in the ammonium application treatment, the rapid consumption of $O_2$ in the soil was accompanied by the production of NO and $N_2O$. Especially in the period of aerobic to anaerobic transition, the production of NO and $N_2O$ showed an increase of nearly 5 times. In the ammonium with ammonia oxidizing bacteria (AOB) inhibitor treatment, the $O_2$ consumption of soil decreased to the same level as that of control treatment. The production of NO and $N_2O$ was almost completely inhibited. Nitrogen application caused simultaneous expression of nitrification (amoA, amoB, and hao) and denitrification (nirK, narG, and narH) genes in the early aerobic phase, and increased expression of denitrification (nirS, norB, and nosZ) genes in the late anoxic phase. Moreover, the expression of some genes activated in the early stage (such as hao, narG and narH) remained until the late stage, which was consistent with the high emission of $N_2O$. AOB inhibitors significantly inhibited the gene expression in the early aerobic stage (amoA, amoB, hao, nirK, narG and narH) and the late anoxic stage (norB), but the inhibitory effect on amoA, amoB and nirK genes gradually decreased with the extension of culture time. This indicates that the consumption of soil $O_2$ by strong ammonia oxidation is an important driving force of $N_2O$ production, with subsequent coupled processes such as hydroxylamine oxidation-reduction, nitrite reduction, nitrate reduction, and nitric oxide reduction occurring synchronously. Coupled expression of nitrification and denitrification genes during $O_2$ consumption was a major reason for the high $N_2O$ emissions from strong ammonia oxidation. Our results provide new evidence for understanding the microbial mechanism of high $N_2O$ emission caused by strong ammonia oxidation.

**Acknowledgments**

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# Effects of Elevated $CO_2$ Concentrations and Temperature on Soil Inorganic Nitrogen and Greenhouse Gas Emissions in Winter Wheat

**ABSTRACT**

The response of greenhouse gas emissions from farmland soils to climate change is a prominent issue in the realm of agricultural adaptation to climate change. This experiment investigated the effects of elevated $CO_2$ concentration and temperature on greenhouse gas emissions from winter wheat soil. Measurements included the contents of nitrate nitrogen and ammonium nitrogen in the winter wheat soil under conditions of elevated $CO_2$ concentration (600 μmol/mol) and elevated temperature (ambient temperature +2°C), as well as greenhouse gas emission fluxes and cumulative seasonal emissions. The global warming potential (GWP) and greenhouse gas emission intensity (GHGI) for the growing season were calculated in conjunction with winter wheat yield. The results showed that under elevated $CO_2$ concentration and temperature, soil nitrate nitrogen content increased significantly at the jointing stage. Soil ammonium nitrogen content increased to varying degrees across three growth periods under these conditions. Compared to the control (T0C0), the cumulative seasonal $CO_2$ emissions under warming alone (T1C0), elevated $CO_2$ alone (T0C1), and the combined treatment (T1C1) increased by 20.73%, 22.18%, and 23.28%, respectively. However, the cumulative seasonal $N_2O$ emissions increased significantly only under T0C1, while decreasing by 26.35% and 18.41% under T1C0 and T1C1, respectively, compared to T0C0. The cumulative seasonal $CH_4$ uptake under T1C0 decreased significantly by 93.56% compared to T0C0, while T0C1 and T1C1 had no significant effect. The winter wheat yield under T1C0 decreased significantly by 19.93% compared to T0C0, whereas it increased by 15.36% and 9.88% under T0C1 and T1C1, respectively. The GWP under T1C0, T0C1, and T1C1 increased significantly compared to T0C0. The GHGI increased significantly under T1C0 compared to T0C0, while it decreased under T0C1 and T1C1, though not significantly. In summary, under conditions of elevated $CO_2$ concentration and temperature, the cumulative seasonal emissions of $CO_2$ and $N_2O$ changed to varying degrees, while the cumulative seasonal $CH_4$ uptake decreased significantly under warming treatment. The projected GWP from the three greenhouse gases in the wheat field is environmentally unfavorable. This study provides an estimation of greenhouse gas emissions from northern wheat fields under conditions of elevated $CO_2$ and temperature, offering theoretical support for formulating future agricultural emission reduction measures.

**Keywords:** Wheat field; Greenhouse gases; Climate change; Global warming potential (GWP); Greenhouse gas emission intensity (GHGI)

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# Evaluation of Greenhouse Gas Emission Characteristics by the Use of Organic Resources and No-Tillings in Organic Agricultural-Based Corn Plantations

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**ABSTRACT**

As climate change driven by global warming accelerates, the world is facing an increasingly severe climate crisis. These changes are primarily attributed to the continuous increase in greenhouse gases ($CO_2$, $CH_4$, $N_2O$), among which agriculture is recognized as a major emission source. Although agriculture is essential for food production, excessive fertilizer use and agricultural machinery operations substantially contribute to greenhouse gas emissions. Consequently, developing field-applicable management practices that reduce greenhouse gas emissions from the agricultural sector is a critical challenge for climate change mitigation. No-tillage systems reduce emissions by minimizing soil disturbance, and their mitigation potential is further enhanced when combined with organic amendments. However, comparative evaluations of greenhouse gas emissions and carbon balance under no-tillage conditions using conventional mineral fertilizers and diverse organic amendments remain limited.

This study was conducted in an organic maize field located in Sinbuk-eup, Chuncheon, Korea. Six treatments were established under no-tillage conditions: Control, NPK, Oil_Cake, Compost, Oil_Cake+Green manure (OG), and Compost+Green manure (CG). Greenhouse gas emissions were measured weekly using the static closed chamber method with three replicates per treatment and analyzed using gas chromatography. Based on the measured emissions, Total Global Warming Potential (Total GWP), Net Global Warming Potential (Net-GWP), Net Ecosystem Carbon Balance (NECB), and Greenhouse Gas Intensity (GHGI) were calculated.

Under no-tillage conditions, all organic amendment treatments exhibited lower Total GWP compared to the NPK treatment, with CG showing the greatest reduction. Net-GWP values were more negative in organic amendment treatments, indicating net carbon uptake, and the highest carbon sequestration was observed in CG. NECB was also higher in organic amendment treatments than in the NPK treatment, again peaking in CG. GHGI was lowest in the CG, demonstrating the highest efficiency in reducing greenhouse gas emissions per unit yield.

These results indicate that under no-tillage conditions, cropping systems utilizing organic amendments (NPK, Oil_Cake, Compost) are more effective than conventional mineral fertilizer systems in reducing greenhouse gas emissions, lowering GWP, and improving ecosystem carbon balance while maintaining productivity. In particular, the CG treatment showed the most favorable overall performance. As practical agricultural systems often rely on integrated management strategies rather than single practices, further research is needed to evaluate combined effects of diverse organic amendments and tillage systems.

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# $N_2O$ fluxes after application of organic and mineral fertilizers to acidic tea soils in Kenya

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## ABSTRACT

Kenya is the world's largest tea exporter; the relatively consistent warm and wet climate in the western highlands region allows year-round tea production. Tea plants are grown in acidic soil conditions (pH < 5.0) and typically receive high annual applications of nitrogen (N) fertilizer, in part to replenish the N removed in the harvested leaves. Because the production and application of N fertilizer produce most of the greenhouse gas emissions associated with tea production, there is interest in new methods of meeting the nutritional requirements of tea with lower environmental impacts.

A meta-analysis of fertilizer-induced nitrous oxide ($N_2O$) emissions from tea soils, using data primarily from China and Japan, found a mean fertilizer-induced $N_2O$ emission factor (EF) of 2.31% (Wang et al., 2020) which is notably higher than the standard IPCC $N_2O$ wet-climate EF of 1.6%. However, in a recent paper, we used an established process-based crop-soil model predicting that tea soil acidity suppresses the nitrification-denitrification pathway, leading to lower $N_2O$ emissions (Giannitsopoulos et al., 2023). Hence, the aim of this study is to determine the actual $N_2O$ emissions under field conditions from acidic tea soils in East Africa.

In 2024, we established a field-based experiment in the Kericho region of Kenya, which was designed to examine environmental performance and yield of five fertilizer types: two organic pelletized compost fertilizers, two mineral fertilizers (urea and NPK), and a novel carbon-capture based organo-mineral fertilizer (OMF). These five fertilizers were tested at six different rates (0-450 kg N $ha^{-1}$ yr-1) to explore dose-responses. The five fertilizer treatments had varying carbon-to-nitrogen ratios, and during 2024-2025 the effects of fertilizer application on $N_2O$ emissions were determined using a portable Gasmet analyser.

In contrast to our model predictions, the field observations indicated that $N_2O$ emissions from four of the five fertilizer types were broadly consistent with an EF of 1.6%, although this varied with application rate. This presentation will quantify the observed incremental $N_2O$ emissions across fertilizer types and rates when applied to acidic Kenyan tea soils. It will also propose how these results can be used to update our existing process-based model of $N_2O$ production pathways in acidic soils. This combination of plot-scale measurements with modelling of C and N interactions can therefore be used to create new guidelines to support climate-smart tea production in acidic agroecosystems.

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# Microbial phosphorus cycling: A key driver of $CO_2$ emission in phosphorus-supplied subtropical forest soils

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**ABSTRACT**

Subtropical forests are key global soil organic carbon (SOC) sinks, whose stability is important for mitigating global climate change. Current understandings indicate that phosphorus (P) availability could promote SOC decomposition by alleviating microbial P limitation. However, it is uncertain if this mechanism holds across soils or field-scale P supply levels in acidic subtropical forests where SOC is held stable by iron (Fe) oxides. We formulated an alternative mechanism that: P supply increases its competitive capacity for Fe-binding sites, leading to SOC desorption as dissolved organic carbon (DOC). The DOC satisfies the enormous microbial C need during P cycling to drive $CO_2$ emissions. We utilized a forest P-addition platform to test our hypothesis across four P supply levels: 0, 25, 50, and 100 kg P $ha^{-1}$ $yr^{-1}$, for one year. We found that increasing P supply significantly increased DOC release, Fe-bound P formation, and microbial biomass P (MBP), but not microbial biomass C. The significantly positive relationship between available P and DOC, and between MBP content and $CO_2$ emission, indicated that the released DOC alleviates microbial C need induced during P acquisition, thereby driving $CO_2$ emission. Mixed-effect and multivariate models identified MBP as the primary driver of $CO_2$ emissions. In addition, the insignificant alterations in C-degrading genes and reductions in C-degrading enzyme activity with P supply indicated the sufficiency of the released DOC for microbial use without further significant SOC degradation. Our study provides an alternative mechanism by which P regulates soil C cycling in acidic subtropical forest soils, offering critical insights for improving process-based C models.

**Keywords:** Global change; carbon sequestration, soil organic carbon; phosphorus cycling

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# The Carbon-Iron Coupling Mechanism of Organic Carbon Turnover in the Rice Root Zone Under Redox Gradients

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## ABSTRACT

In paddy soils, the root zone is a hotspot of carbon cycling, where turnover is governed by redox conditions and iron. Yet, how iron mediates organic carbon (OC) mineralization and transformation across these redox gradients remains unclear. We therefore established a simplified rhizosphere microcosm system by using soil columns equipped with artificial roots. Four redox potential gradients of the soil column were constructed by adjusting water conditions (60%, 80%, and 100% of soil water saturation, plus 3 cm flooding), and $^{13}C$-labeled glucose or oxalic acid were used as model root exudates for investigating the iron-mediated OC allocation and transformation. The results showed that: (1) Both soil redox potential (Eh) reduction and exogenous carbon input significantly increased the cumulative emissions of $CH_4$ and $CO_2$. Under 100% saturation and flooding conditions, the incremental emission of $CH_4$ was significantly higher than that of $CO_2$ in glucose- and oxalic acid-amended treatments, and vice versa in the unsaturated water content. Compared with glucose, oxalic acid treatment under flooding conditions induced negative priming effects on both $CH_4$ and $CO_2$ during the early incubation stage. (2) Exogenous carbon inputs elevated the dissolved organic carbon (DOC) content under 60% of soil water saturation. DOC aromaticity responded oppositely to decreasing Eh, it increased under glucose treatment but decreased under oxalic acid treatment. The $^{13}C$-DOC pool displayed a unimodal temporal pattern, reaching its maximum concentration at day 20. A positive correlation was observed between soil Eh and SOC content in all exogenous carbon amendment treatments. The incorporation of $^{13}C$ into the SOC pool was significantly more pronounced with glucose addition relative to oxalic acid. The oxalic acid treatment stimulated the generation of iron-bound OC (Fe-OC), predominantly through the pathway of $^{13}C$ enrichment within the Fe-OC fraction. (3) The activities of carbon cycle hydrolase and oxidase were significantly affected by the redox gradient and simulated rhizodeposited carbon input. Cellobiohydrolase activity decreased with decreasing Eh and showed a negative correlation with $CH_4$+$CO_2$ emission rates. Moreover, phenol oxidative activity was higher in the saturated water treatments than in the unsaturated water treatments and was positively correlated with the rate of gas emission. Glucose and oxalic acid addition significantly increased the activities of phenol oxidative activity and catalase oxidases. Both the “iron gate” and “enzyme latch” mechanisms synergistically regulated $CH_4$ and $CO_2$ emissions. The findings provide critical parameters and a scientific basis for predicting rhizodeposited carbon sequestration potential in subtropical iron-rich paddy soil, and optimizing water management strategies to enhance carbon storage and mitigate greenhouse gas emissions in rice cultivation systems.

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# Effect of soil structure on $N_2O$ production and emission

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**ABSTRACT**

Soil structure regulates the production and emission of nitrous oxide ($N_2O$) from soils mainly through influencing substrate availability and gas transport, which are strongly intertwined with soil moisture. However, the interaction between soil structure and water content in controlling $N_2O$ emissions remains inadequately quantified. This study conducted laboratory incubation experiments with disturbed (sieved) and undisturbed (intact) soil cores under different soil moisture levels (i.e., 40, 60, 80 and 100% water filled pore space (WPFS)). Soil carbon dioxide ($CO_2$) and $N_2O$ fluxes were continuously monitored during the 21-day incubation period, during which $O_2$ concentration profile was occasionally measured and relative soil gas diffusivity was measured at the end of experiments. The results show that the $N_2O$ fluxes from the disturbed soil cores were 2~25 times higher than those from the undisturbed cores, which are similar to field observations. Nevertheless, the difference in the relative soil gas diffusivity between them was not obvious, especially under high moisture conditions. Therefore, the overestimated soil $N_2O$ emission from sieved soil experiments was attributed to increased substrate availability caused by disturbance rather than changes in gas diffusivity. An additional finding of a significant exponential correlation between $N_2O$ and $CO_2$ flux under the same moisture condition, regardless of whether the soil was sieved or intact, further demonstrated that the key impacts of physical protection of organic carbon and thus $O_2$ consumption on soil $N_2O$ emission. Overall, this study highlighted the physical protection of soil aggregates on carbon sequestration and $N_2O$ mitigation.

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# Coupling of nocturnal water vapor and $CO_2$ uptake in arid soils: Comparative analysis from three arid soils

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**ABSTRACT**

Nocturnal water vapor absorption and $CO_2$ uptake by dry soils are widely observed phenomena in arid ecosystems. Although empirical evidence suggests a correlation between these processes, the nature of their relationship, whether causal or coincidental, remains unclear. One hypothesis is that water vapor absorbed at night provides sufficient moisture for $CO_2$ dissolution and subsequent reactions with soil carbonates, thereby facilitating $CO_2$ uptake. Alternatively, $CO_2$ fluxes may be governed by physical processes, such as diurnal temperature-driven air expansion and contraction. Understanding the link between water vapor absorption and $CO_2$ uptake is crucial for understanding hydrological–carbon cycle interactions in drylands and improving predictions of global carbon dynamics. However, direct evidence of water vapor input influencing $CO_2$ uptake is limited. In this study, we combine field work and modeling to examine the role of water vapor input in driving $CO_2$ uptake by comparing (1) two sites with similar soil textures but differing distances from the sea, and (2) two sites with similar proximity to the sea but different soil textures. Our results showed that the site closer to the sea absorbed more water vapor and exhibited greater $CO_2$ uptake. In contrast, although the site with finer-textured soil absorbed more water vapor, it did not show greater $CO_2$ uptake. These results suggest that the mechanisms governing $CO_2$ uptake may vary across sites. While geochemical processes modulated by water vapor absorption could be a major mechanism, other mechanisms—such as thermal convection—may play a significant role, particularly in soils with higher permeability.

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# Carbon Flux Responses of Rice Paddy to Coupled Heatwaves and Droughts in the Jianghan Plain

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**ABSTRACT**

Rice paddies are a globally significant agricultural ecosystem: they supply a major portion of human food and play an important role in regional and global carbon cycles and greenhouse-gas budgets. Climate change strongly regulates the farmland carbon cycle, yet the influence of extreme temperature events on carbon fluxes across subtropical Chinese farmland remains poorly characterized. Our objectives are to quantify how heatwaves (*HW*), Drought, and their co-occurrence modulate water and carbon fluxes in subtropical paddy fields. Continuous meteorological and eddy-covariance observations (2021–2024) were coupled with XGBoost-SHAP analyses, generalized additive models (*GAMs*), and nonparametric tests, including the Kruskal-Wallis test (net ecosystem exchange (*NEE*) $p < 0.01$; ecosystem respiration (*Re*), water-use efficiency (*WUE*), evapotranspiration (*ET*) $p < 0.001$; gross primary productivity (*GPP*) not significant), to identify dominant drivers, nonlinear thresholds, and flux responses under four climatic regimes (Normal, HW, Drought, HW-Drought). The paddy system acted as a persistent carbon sink, with strong NEE uptake and annual cumulative NEE of−492.10、−463.10、−547.26 and −532.73 g C $m^{-2}$ in 2021–2024 rice growth period. Compound HW-Drought events substantially weakened sink strength: mean daily NEE was least negative under HW-Drought (−3.59 ± 4.79 g C $m^{-2}$ $d^{-2}$) versus Normal (−6.31 ± 4.03 g C $m^{-2}$ $d^{-1}$), while RE increased and GPP remained comparatively stable. ET rose and WUE declined under compound stress (ET in HW-Drought = 5.97 ± 0.97 mm $d^{-2}$; WUE: Normal = 3.09 ± 0.97 vs HW-Drought = 2.43 ± 0.42 g C $kg^{-2}$). XGBoost-SHAP captured major flux variability (NEE $R^2 = 0.933$; Re $R^2 = 0.801$; ET $R^2 = 0.906$) and identified incoming solar radiation (*Rg*) as the primary control on NEE and ET, with air temperature (*Ta*) and soil volumetric water content (*SWC*) dominating Re. GAMs fitted to SHAP responses revealed nonlinear thresholds (e.g., Rg ≈ 116 W $m^{-2}$ and RH ≈ 67% for NEE; Ta breakpoints and SWC ≈ 0.425 $m^3$ $m^{-3}$ for Re) where predictor effects reversed sign. Overall, compound hot-dry extremes may disproportionately boost respiration relative to photosynthesis, potentially reducing carbon sequestration while increasing evaporative loss. We discuss adaptive field management (precision water regulation, heat-/drought-tolerant cultivars) to bolster paddy resilience and sustain carbon-sink function under intensifying extreme climate regimes.

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# No tillage reduces nitrous oxide emissions in Winter and early Spring globally

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## ABSTRACT

As a core Climate-Smart Agriculture (CSA) practice, conservation tillage significantly mitigates nitrous oxide ($N_2O$) emissions. Although freeze-thaw cycles during winter-early spring trigger substantial $N_2O$ pulse emissions, the mitigation potential of conservation tillage during this period remains unquantified. Through a global meta-analysis of 62 publications, this study demonstrates that: (1) Conservation tillage (no-till and reduced tillage) reduced $N_2O$ emissions by 16% during the winter-early spring period; (2) No-till achieved a significant reduction of 18%, whereas reduced tillage showed no statistically significant effect; (3) Climatic factors (mean and minimum temperatures of the coldest quarter), soil properties (soil texture and SOC), and the duration of no-till implementation were identified as key factors influencing the mitigation efficacy of no-till. In contrast, precipitation in the coldest quarter and nitrogen input exhibited no independent effects, likely suppressed by seasonal low temperatures. This study provides valuable data to support the development of $N_2O$ mitigation frameworks in agricultural systems and contributes to informing effective strategies for controlling global agricultural $N_2O$ emissions and mitigating the greenhouse effect.

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# Organic amendments regulated the pattern and product stoichiometry of nitrate reduction processes in arable soils

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**ABSTRACT**

Organic amendments are widely recognized for improving soil health and multifunctionality in agroecosystems, yet their effects on nitrate reduction pathways and associated soil greenhouse gas emissions remain poorly understood. We show that organic amendments in upland arable soils increased the contribution of fungal denitrification to total $N_2O$ emissions while lowering the $N_2O/(N_2O+N_2)$ ratio, primarily by strengthening fungal–bacterial mutualistic interactions among denitrifiers. The magnitude and partitioning of $N_2O$ and $N_2$ emissions were further regulated by soil nitrate availability. In flooded paddy soils, biochar application significantly reduced $N_2O$ fluxes and $N_2O/(N_2O+N_2)$ ratios, driven by shifts in the abundance and composition of nitrate-reducing microbial communities. Biochar simultaneously increased denitrification and dissimilatory nitrate reduction to ammonium (DNRA) rates, and shifted more $NO_3^-$ partitioning toward DNRA process. These effects were mainly attributable to enhanced carbon availability and altered nitrate-reducer community structure. Collectively, our results demonstrate that organic amendments in arable soils can mitigate the environmental impacts of nitrogen fertilization by regulating nitrate reduction pathways, thereby advancing our mechanistic understanding of nitrogen cycling in agroecosystems.

# Root Exudate Chemistry Drives Divergent Carbon Fates in Rice Paddies

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**ABSTRACT**

Paddy ecosystems play a dual role in climate change, acting as significant sources of methane ($CH_4$) emissions while possessing substantial carbon sequestration potential. Root exudates, the primary carbon input, critically influences both soil organic carbon (SOC) stability and $CH_4$ emission, yet the underlying mechanisms remain poorly understood. This study employed continuous $^{13}C$ labeling of two contrasting rice cultivars, a conventional japonica (CXJ) and a hybrid japonica (HZY), to trace the flow of root carbon and its impact on $CH_4$ dynamics. A key finding was that the cultivar with higher biomass and root carbon input (HZY) did not result in elevated $CH_4$ emissions.

Metabolomic profiling of root exudates revealed fundamentally divergent strategies. CXJ roots were enriched in the glyoxylate and dicarboxylate metabolism pathway, leading to secretion of labile organic acids like citric acid. These compounds rapidly decompose in soil to provide acetate, a direct precursor for methanogenesis, explaining the higher $CH_4$ emissions in CXJ. In contrast, HZY roots exhibited a coordinated “chemical suppression” strategy, with enrichment in pathways for glucosinolate and cyanoamino acid. The associated exudates, such as isothiocyanates, thiocyanates, and riboflavin, may divert microbial electron flow towards competitive processes like sulfate reduction, potentially mitigating the emission risks from its substantial carbon input. The distinct fate of root carbon was corroborated by soil $^{13}C$ partitioning. Soils under HZY accumulated more $^{13}C$ in the mineral-associated organic carbon (MAOC) fraction, indicating a direct, abiotic pathway to stabilization. Correspondingly, soils under CXJ showed greater $^{13}C$ enrichment in microbial residual carbon, indicating an indirect, microbially mediated pathway that first fuels microbial growth and turnover before entering the stable pool.

Our results demonstrate that root exudate chemistry critically determines the fate of root carbon, either promoting its long-term mineral stabilization or facilitating its microbial conversion to $CH_4$. Targeting root exudate profiles that promote biochemical suppression of methanogenesis and direct mineral association could enable the dual goals of enhancing soil carbon storage and reducing greenhouse gas emissions from paddy ecosystems.

# Contrasting warming responses of anaerobic microbial communities explain variation in methane Q10 across paddy soils

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## ABSTRACT

Rice paddies are among the largest anthropogenic sources of methane ($CH_4$), yet large uncertainties remain in predicting how $CH_4$ production responds to warming across different climatic regions. In particular, the microbial processes underlying variation in the temperature sensitivity (*Q10*) of $CH_4$ production are still poorly constrained. To address this, we investigated warming responses of anaerobic $CH_4$ production and associated microbial functions in paddy soils originating from contrasting mean annual temperature (MAT) regimes.

Soils were collected from four rice-growing regions in China spanning low (4–9°C) and high (14–16°C) MATs and incubated anaerobically at 15°C and 30°C. $CH_4$ production, dissolved organic carbon, and fermentation products were quantified, and microbial communities were characterized using quantitative PCR, amplicon sequencing, genome-resolved metagenomics, and metatranscriptomics.

Methane production showed consistently higher *Q10* values in soils from low-MAT regions, whereas soils from high-MAT regions exhibited stronger warming-induced changes in microbial composition and functional gene expression. Across all soils, higher *Q10* values coincided with lower abundances of genes involved in polysaccharide depolymerization, hydrogenotrophic methanogenesis, and reduced average genome size, indicating limited microbial capacity for rapid carbon turnover. In contrast, pathways related to fermentation and acetate metabolism became relatively more prominent at higher *Q10* values. Transcripts associated with methylotrophic methanogenesis declined under warming in all soils, while acetoclastic and hydrogenotrophic pathways responded differently depending on MAT origin.

Together, these results show that variation in the temperature sensitivity of $CH_4$ production reflects differences in how anaerobic microbial communities process organic carbon under warming, rather than uniform temperature effects. Accounting for microbial functional organization across climatic gradients is therefore critical for improving predictions of soil methane emissions in a warming climate.

**Key words:** Methane *Q10*; Carbon turnover; Methanogenesis pathways; Paddy soils

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# Slowing down the strong ammonia oxidation is the key to reduce $N_2O$ emission in alkaline agricultural soils

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**ABSTRACT**

Slowing down the strong ammonia oxidation is the key to reduce $N_2O$ emission in alkaline agricultural soils.

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# Effects of three differently activated biochars on greenhouse gas emissions from a fertile clay loam in boreal conditions

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## ABSTRACT

Nutrient-enriched biochars could add value to raw biochars by enhancing nitrogen bioavailability. However, their effects on greenhouse gas emissions (GHG) from soil and crop growth in boreal regions remain unclear. We aimed to investigate the impacts of three different types of activated biochar: cattle slurry-enriched biochar ($BC_{org}$), mineral fertilizer-enriched biochar ($BC_{min}$), and pure water-activated biochars ($BC_{wat}$), on GHG emissions, including carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$) from a fertile boreal Stagnosol with a clay loam texture. For this purpose, we added activated biochars to a long-term biochar field experiment (est. 2010) at the University of Helsinki's research farm in Helsinki, Finland. The initial experimental design consisted of three separate split-plot field experiments (subfields) in the same field area, each with four replications, with biochar rates of 0, 5, and 10 Mg/ha added to the main plots, and different N fertilizer levels (30%, 65%, or 100% of the recommended level) applied to the subplots. A similar setup was now used in our study, except that we added 15 Mg/ha of activated biochars to plots that had previously received 5 Mg/ha. Thus, each subfield was treated with one type of activated biochar, followed by a three-year crop rotation of barley (2023), faba bean (2024), and spring wheat (2025). Emissions of $CH_4$, $CO_2$, and $N_2O$ were measured 8 times after sowing, using a closed chamber method with two cylindrical metal chambers installed on plots treated with new biochar and on control plots. Upon sampling, a 2 × 5 mL gas sample was drawn and injected into a pre-evacuated gas vial at 0, 20, and 40 minutes after closing the chamber. The temperature inside each chamber was recorded. The concentrations of $CH_4$, $CO_2$, and $N_2O$ in the collected samples were determined by a gas chromatography system (Agilent 7890B GC System). Average $CO_2$ emissions were highest in 2023 compared to 2024 in all treatments, due to the freshly added biochars in 2023. $BC_{wat}$ resulted in decreased $CO_2$ emissions ($p < 0.05$) only during the early vegetative growth phase (2-3 weeks after sowing) in both years. The slight reductions in mean $CO_2$ emissions by $BC_{min}$ were mostly not significant except for a week in June 2024 following a period of heavy rain. Average $CO_2$ emissions were generally reduced by the addition of $BC_{org}$ ($p < 0.05$, in 3-4 weeks after sowing) in 2023, but increased in 2024. Mean $N_2O$ emissions were generally lower in 2024, because faba bean required less fertilizer input relative to barley (2023). $BC_{org}$ and $BC_{min}$ increased $N_2O$ emissions in 2023 (p-values < 0.05) during the early vegetative phase only (1-3 weeks after sowing), but no significant effects were observed in 2024. Adding $BC_{wat}$ did not affect $N_2O$ emissions. Emissions of $CH_4$ were generally not affected by any of the treatments. The full results on the impact of the differently activated biochars on GHG emissions will be detailed in the poster.

# Inhibition and the mechanisms of ethene on methanogen

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**ABSTRACT**

Anaerobic environments function as both a source and a sink within the global methane cycle, with microbially produced methane contributing over half of the annual atmospheric methane emissions. During bioremediation of chlorinated ethenes contamination, substantial ethene accumulation occurs, and almost inhibited methanogenesis, which are key processes in anaerobic systems. This study systematically elucidates the inhibitory mechanism of ethene on methanogenesis, employing *Methanosarcina barkeri* Fusaro as a model methanogen, and methanogenesis consortia enriched from river sediments. We demonstrate a clear dose-dependent and pathway-specific inhibition by ethene. In pure culture, ethene selectively suppressed acetoclastic methanogenesis compared with methylotrophic methanogenesis. Without ethene, methane production by *M. barkeri* Fusaro peaked at 956.2 ± 111.4 μmol by day 25. At 0.33% ethene in the gas phase, the methanogenesis period extended to 50 days without significant reduction in final yield. Increasing ethene to 1.67% reduced methane production to 189.63 ± 61.42 μmol over 60 days, while 3.33% ethene completely inhibited activity throughout the incubation of 100 days. Proteomic analysis indicated that at 0.83% ethene in gas phase, expression of the acetyl-CoA decarbonylase/synthase complex (CODH) and the methyl-coenzyme M reductase alpha subunit (McrA), which are key enzymes in the acetoclastic methanogenesis pathway were up-regulated by approximately 22-fold and 2-fold, respectively, concurrent with a prolonged methanogenesis period. This suggests ethene likely disrupts enzymes activity, potentially via interaction with nickel/iron sulfur cofactors. In sediment-free microcosms (fourth transfer), the ethene-free cultures reached maximum methane production (5080.4 ± 250.2 μmol) by day 7. In contrast, with 6.67% ethene, production peaked later (day 20) at a lower level (3945.2 ± 354.4 μmol), indicating suppression of both the rate and total yield of methanogenesis. Ethene also markedly shifted methanogens community structures: methylotrophic methanogens (e.g., *Methanomethylovorans*) declined, whereas hydrogenotrophic methanogens (e.g., *Methanosarcina*) became more dominant. These findings deepen our understanding of environmental stress responses in methanogens and offer a scientific basis for evaluating and mitigating ecological risks during anaerobic bioremediation of organohalide contamination sites.

**Key words:** methanogen, ethene, methane, inhibition, *Methanosarcina*

# Static Chamber Protocol Optimization for Soil Greenhouse Gas Flux Measurements under Pulse Events

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## ABSTRACT

Static closed chambers coupled with gas chromatography are widely used to quantify soil greenhouse gas fluxes. Standardized guidance remains limited for key protocol elements, including chamber volume, closure duration, and mixing conditions. This uncertainty is particularly consequential for short-lived nitrous oxide ($N_2O$) emission pulses triggered by fertilization or rewetting, which can contribute disproportionately to annual budgets. Here, static chamber protocols were evaluated in a subtropical forest soil with an emphasis on resolving event-scale $N_2O$ dynamics.

A factorial field experiment was implemented to quantify the interactive effects of chamber volume, closure duration, and fan operation. Chambers with volumes of 10, 20, and 30 L were deployed. High frequency concentration time series of $N_2O$, carbon dioxide ($CO_2$), and methane ($CH_4$) were measured using a laser-based analyzer, and discrete gas samples were analyzed by gas chromatography under both background conditions and periods with pulse emissions. Protocol performance was assessed using a Flux Credibility Index that integrates goodness of fit, temporal responsiveness, and structural suitability.

Clear trade offs emerged between design parameters and flux resolution. Closure duration strongly affected the ability to resolve event-scale $N_2O$ peaks. Short closures reduced temporal representativeness during the rapid phase after fertilization, whereas long closures increased non-linear behavior and widened differences between online and offline flux estimates. Among the tested configurations, the 20 L chamber provided the most consistent balance by limiting non-linear feedback while retaining sufficient detection sensitivity. These findings support scenario-specific recommendations that align chamber design with monitoring objectives. Overall, protocol harmonization is essential for reducing uncertainty in soil greenhouse gas budgets and enabling robust comparisons across study sites.

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# Microbial regulation of soil $CO_2$ and $CH_4$ emissions during rewetting of degraded peatlands

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## ABSTRACT

Peatlands are major terrestrial carbon reservoirs, and their hydrological degradation and restoration can substantially alter soil carbon transformation processes and associated climate feedbacks. However, the magnitude of carbon emission responses and the underlying microbial regulatory mechanisms following rewetting remain highly uncertain. Here, we conducted a three-year (2023–2025) in situ field study across natural peatlands (NP), rewetted peatlands (RP), and drained peatlands (DP) in degraded peatlands of the Changbai Mountains, Jilin Province, China. We quantified cumulative soil carbon dioxide ($CO_2$) and methane ($CH_4$) emissions and integrated metagenomic analyses with structural equation modeling (SEM) to elucidate hydrological–microbial controls on carbon emissions during the rewetting process.

Across three consecutive years, cumulative soil $CO_2$ and $CH_4$ emissions differed markedly in magnitude and temporal patterns among hydrological regimes, while interannual trends were generally consistent. Cumulative $CO_2$ emissions in NP ranged from 327.90 to 631.81 kg C $ha^{-1}$, which were overall lower than those in DP (441.90–1217.02 kg C $ha^{-1}$), whereas $CO_2$ emissions in RP (353.55–513.66 kg C $ha^{-1}$) consistently fell between NP and DP. These results indicate that drainage persistently enhanced peat soil $CO_2$ release, while rewetting effectively mitigated drainage-induced $CO_2$ emissions over the three-year period, although recovery to natural levels was not achieved. In contrast, $CH_4$ emissions remained consistently high in NP (203.26–297.23 kg C $ha^{-1}$) and were substantially greater than those in RP (11.24–80.51 kg C $ha^{-1}$) and DP (36.41–88.09 kg C $ha^{-1}$), demonstrating that long-term drainage strongly suppressed methanogenesis and that short-term rewetting only partially restored anaerobic conditions, insufficient to recover $CH_4$ emissions to natural peatland levels. Taken together, the net climate effect of peatland rewetting, characterized by the 100-year global warming potential ($GWP_{100}$), is governed by trade-offs between $CO_2$ reduction and $CH_4$ enhancement.

Microbial analyses revealed that hydrological disturbance regulated methane cycling primarily through shifts in functional potential rather than pronounced taxonomic replacement. The methanogenesis marker gene mcrA maintained high abundance in NP but was strongly suppressed under long-term drainage, with RP generally exhibiting an intermediate state indicative of pronounced hydrological legacy effects. In contrast, methane oxidation–related functions exhibited more complex and depth-dependent responses to water table recovery. Metabolic network analyses further showed that drainage reduced the relative contribution of methanogenesis-related modules within the overall metabolic network, promoting functional allocation toward non-methanogenic pathways, whereas rewetting partially restored the dominance of methanogenic pathways in deeper soil layers, while surface soils retained clear drainage characteristics. SEM results collectively indicated that water table position and temperature indirectly regulated $CO_2$ and $CH_4$ emissions by modulating organic carbon availability and key microbial functional groups, highlighting the coupled control of hydrological conditions and microbial processes during rewetting.

Overall, rewetting substantially alleviated drainage-induced $CO_2$ emissions and partially restructured methane cycling functional networks over the three-year period, yet the recovery of carbon emission magnitude and associated climate effects remained constrained by strong hydrological legacy effects. This study provides robust field-based evidence for understanding carbon emission dynamics and microbial mechanisms during peatland rewetting and offers important implications for climate-oriented wetland restoration.

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# Effect of soil structure on $CO_2$ production and emission

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**ABSTRACT**

Soil structure, as the fundamental physical architecture, regulates the production and emission of carbon dioxide ($CO_2$). The effect of soil structure is likely most important but least quantified, mainly due to the difficulty of its direct measurement and the concealment of microscale heterogeneity. Laboratory incubation experiments with disturbed (sieved) and undisturbed (intact) soil cores under different soil moisture levels showed that soil structure disruption (sieving) significantly increased $CO_2$ emissions compared to intact soil. This phenomenon is mainly attributed to the physical protection conferred by the intact soil structure, which constrains the accessibility of substrates (such as organic matter and oxygen) to microorganisms. It was further supported by the evidence derived from X-ray computed tomography that more effective reaction zones (the spatial domains where substrate diffusion flux exceeds microbial consumption flux) can be identified in sieved soil than in intact soil. These findings bridge the gap between macroscopic $CO_2$ fluxes and microscale heterogeneity. Overall, it is necessary to include such key quantifiable physical indexes in future soil carbon models, which is critical to interpret and predict macroscopic soil processes and functions.

# Belowground Cross-trophic Networks Impact $CH_4$ and $CO_2$ Emissions in Degraded Alpine Peatlands

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**ABSTRACT**

Belowground organisms forming complex cross-trophic ecological networks are essential for maintaining peatland carbon stability and energy flow. However, how peatland degradation affects the biodiversity and cross-trophic ecological netowrks of soil communities remains poorly understood. Here, we examined the degradation effects on soil prokaryotes (i.e., bacteria, archaea), fungi and nematodes in alpine peatlands on the eastern Tibetan Plateau, characterized by varying water table depths (indicating degradation levels). We found that peatland degradation, accompanied by significant shifts in soil moisture and pH ($P$ <0.05), reduced the taxonomic richness and phylogenetic diversity of prokaryotes, fungi, and nematodes, particularly in deeper soil layers (20-50 cm). Crucially, peatland degradation weakened potential cross-trophic interactions within bipartite networks of prokaryotes-nematodes and fungi-nematodes, resulting in less than 6.5%-28.8% of unchanged modules. Degradation-induced changes in soil moisture and pH were identified as primary drivers of biodiversity loss and network restructuring. Furthermore, such changes of belowground cross-trophic networks (particularly prokaryote-nematode) were significantly correlated with greenhouse gas emissions, such as decreased $CO_2$ emissions, maintained $CH_4$ emissions (leading to a higher $CH_4/CO_2$ ratio in deep layers), and reduced temperature sensitivity ($Q_{10}$) of soil respiration. These findings underscore the critical need to protect soil biodiversity and cross-trophic netowrks in peatlands, particularly under the threat of climate change, to preserve peatland carbon stocks and maintain ecosystem stability. Our findings highlight that belowground cross-trophic netowrks are pivotal to decipher soil carbon dynamics of degraded peatlands and project the fate of peatland carbon stocks under future climate change scenarios.

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# Soil carbon quality modulates the responses of soil respiration and its heterotrophic and autotrophic components to fertilization under straw return and extreme rainfall

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## ABSTRACT

Soil respiration (Rs) is the dominant pathway returning carbon (C) as carbon dioxide ($CO_2$) from croplands and a key uncertainty in managed-soil C budgets. Partitioning Rs into heterotrophic respiration (Rh, derived from microbial decomposition of organic matter) and autotrophic respiration (Ra, derived from live plant roots and associated rhizosphere microorganisms) is essential because these components represent distinct processes that can respond independently, or even oppositely, to environmental change. Rs is governed by the coupling of substrate properties, nutrient availability, and hydrologic constraints, yet how these drivers interact to regulate Rh and Ra remains poorly constrained, particularly when straw return and extreme rainfall reshape the context of nutrient effects. Here we integrated complementary field experiments in northeast China using paired croplands with comparable soil organic C quantity but contrasting C quality (high vs. low), and quantified annual Rs, Rh, and Ra under six harmonized treatments (CK, NF, PF, NP, SR, SRF) spanning nutrient additions, straw return, and a contrast between normal and extreme rainfall years. Overall, the high-C-quality soil maintained higher Rs mainly through stronger Rh, consistent with greater substrate C bioavailability and enhanced microbial C-acquisition activity, whereas Ra tracked plant nutrient status and inorganic N supply. Nutrient additions and straw return did not exert uniform effects but were filtered by C quality: in high-C-quality soils, N inputs tended to suppress microbial $CO_2$ release by shifting microbial metabolism from mineralization toward assimilation, while in low-C-quality soils, responses were weaker and aligned with continued microbial nutrient mining under substrate limitation. Straw return generally amplified Rh by providing fresh residues and stimulating hydrolytic processing, yet co-supplied nutrients reshaped this stimulation by lowering straw-induced mineralization and increasing the potential stabilization efficiency of straws in C-quality-dependent ways. In contrast, extreme rainfall imposed hydrologic limitation, such that elevated soil moisture and waterlogging suppressed enzymatic decomposition and diminished the advantage of high C quality in Rh, whereas Ra remained comparatively governed by mineral N availability. Together, these results identify C quality as an overarching driver determining whether nutrient supply enhances, constrains, or redistributes microbial and plant contributions to Rs, and show that straw return and extreme rainfall shift the balance among physical, chemical, and biological controls on cropland $CO_2$ emissions. This synthesis supports C-quality-stratified fertilization and straw management under increasingly frequent extreme rainfall and improves the interpretability of $CO_2$ flux responses in managed soils.

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# Effects of Three-Dimensional Surface Area Correction on Soil $CO_2$ Flux and Biomass Accounting in a Gully Landscape

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**ABSTRACT**

Soil $CO_2$ flux and biomass accounting in complex gully landscapes is commonly based on two-dimensional (2D) projected area together with slope-based stratification. This practice does not represent true three-dimensional (3D) surface geometry or topographic heterogeneity within land-use units, potentially introducing area-scale bias into regional carbon budget estimates. Here, we investigated a representative gully system (Xiaohegou sub-catchment) in the Wangdonggou watershed on the Chinese Loess Plateau. A high-resolution 3D terrain model was derived from winter UAV–LiDAR, and summer UAV multispectral imagery and point-cloud information were integrated to support gully-scale 3D land-use classification using a Random Forest approach. Land-use labels were mapped onto ground point clouds, and 3D surface areas for each land-use type were computed using a triangulated irregular network (TIN) to correct 2D area estimates. In situ soil $CO_2$ flux measurements and aboveground biomass estimates across land-use types were used to evaluate how 3D area correction affects carbon accounting.Results show that:(1) Differences between 2D and 3D area increase with slope and terrain fragmentation; the largest increases occur on steep gully-wall units, where local area correction factors exceed **3.5**.(2) Treating land-use types as 3D spatial units reveals pronounced within-type heterogeneity in slope composition; a single type can include microtopographic elements beyond empirically defined “suitable” slope ranges, indicating that slope-only stratification cannot ensure area-scale consistency.(3) Surface-area correction changes the magnitude of area-normalized estimates, thereby affecting calculated soil $CO_2$ emission intensity and aboveground biomass; the associated errors are concentrated in steep and fragmented units.Accordingly, extending accounting units from 2D patches to 3D land-use units and applying 3D surface-area correction can help reduce uncertainty in carbon accounting and improve regional carbon budget assessment in complex terrain.

**Figure 1:** 3D Classification and 2D Visualization of Different Land Use Types



**Figure 2:** In-situ Monitoring of Temperature, Humidity, and $CO_2$ under Different Land Use Types



**Figure 3:** Schematic Diagram of the Research Concept



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# Mechanistic controls of nitrous oxide emissions revealed by flux-gradient measurements and site-specific incubations

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## ABSTRACT

Agricultural soils account for 30% of all global emissions of nitrous oxide ($N_2O$), a potent greenhouse gas with 265 times the global warming potential of carbon dioxide ($CO_2$) (Environment and Climate Change Canada, 2022; IPCC, 2023). Despite many advancements in the fertilizer management sector, $N_2O$ emissions remain highly variable from region to region, highlighting the link between soil physical, chemical, and biological characteristics and $N_2O$ fluxes. Specifically, it remains unclear how soil moisture interacts with soil texture to influence $N_2O$ production pathways including nitrification and denitrification. To address this gap, we integrated continuous ecosystem-scale $N_2O$ flux measurements from 8 agricultural micrometeorological sites across Canada with a controlled soil incubation experiment associated with each site. Field scale $N_2O$ measurements were made using a flux-gradient approach in fields under contrasting best management practices (BMPs) suited for each region. Complementary 24-hour laboratory incubations were conducted using unamended soil from each site, set at water-filled pore space (WFPS) ranging from 40% to 105% WFPS. Isotopomer signatures of $N_2O$ (site pReferences, $\delta^{15}N$, $\delta^{18}O$) were used to determine relative contributions of nitrification- and denitrification-associated $N_2O$ across moisture levels. In field and laboratory experiments, soil moisture emerged as a clear regulator of the magnitude of $N_2O$ flux, but the incubation identified moisture as being a key regulator of the $N_2O$ source pathway as well. The relationship between moisture, SP and $N_2O$ production was highly variably from site to site due to soil texture differences, with heavier clay soils promoting anaerobic conditions and initiating a more rapid pathway change to dominant denitrification at lower moisture levels. Soils with lighter textures produced lower emissions, mostly originating from the nitrification pathway and switched to denitrification over a wider range of moisture and typically at higher WFPS levels. This texture-moisture influence on dominant $N_2O$ pathway coincides with the efficacy of field-scale trials showing denitrification targeted BMPs are most effective at reducing emissions at sites with heavier soils, whereas controlling nitrification is a priority at lighter-textured sites. By explicitly linking field-scale flux-gradient measurements with site-specific, isotopomer-signatures from soil incubations, this study advances our mechanistic understanding of $N_2O$ emissions and identifies soil moisture-texture interactions as critical leverage points for climate-smart fertilizer management under increasing environmental variability.

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# Iron-carbon coupling mechanisms during soil organic carbon dynamics under climate-change conditions in long-term biochar-amended soils

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## ABSTRACT

Soil organic carbon (SOC) is pivotal for both agricultural activities and climate change mitigation, and biochar amendment (BA) stands as a promising strategy to enhance SOC sequestration and curb $CO_2$ emissions. However, in agricultural soils with a long-term BA, the roles of biochar in SOC cycling, and its mediation of interactions among microbes, minerals (especially iron (Fe) oxides) and fresh organic matter (FOM) remain largely unclear, particularly under changing environments. To address this gap, we conducted two-step microcosm experiments of soils with and without a decade-long BA history, adding straw as FOM while mimicking different environment conditions.

During a 56-day incubation at constant temperature (25°C) and moisture (60% water holding capacity), long-term BA had reduced FOM-stimulated $CO_2$ emissions by ~11% during, while enhanced SOC accrual. These effects were highly associated with microbially driven Fe reduction and subsequent Fenton-like reactions, where biochar strengthened Fe cycling, extracellular electron transfer, and microbial carbon use efficiency. The enrichment of Fe-C associations on biochar surfaces suggested microscale hotspots for Fe-C complexation, SOC protection and microbial C sequestration. Supplementary soil-slurry experiments with sterilization and Fe(II) spiking further confirmed that microbes were key triggers of hydroxyl radical (•OH) formation while their assimilation of •OH oxidated organic C was elevated in biochar-amended soil (Supporting figure).

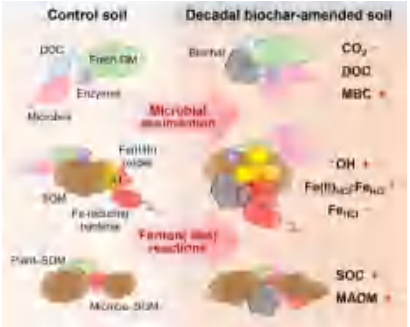
To further resolve C turnover mechanisms under climate-change scenarios, we implied $^{13}$C-labelled FOM and incubated soils under elevated temperature (warming, 30°C) and dry–wet cycles (DWC) conditions. Overall, BA soil consistently showed lower total $CO_2$ emissions than control soil, mainly due to suppressed mineralization of native SOC, whereas the mitigation of FOM-derived $CO_2$ emissions was partly diminished by warming and DWC. Specifically, warming enhanced microbial metabolism but reduced C use efficiency, thereby stimulating SOC mineralization, especially from FOM. Intriguingly, newly formed mineral-associated organic carbon (MAOC) increased in the control soil but not in the BA soil, indicating that temperature and biochar jointly modulate the balance between microbial C turnover and the formation of high–organic-carbon-affinity minerals. Under DWC, rewetting tended to mobilize MAOC and FOM, following drought constrained microbial activity and cumulative C mineralization. Overall, these patterns suggest that MAOC may be less stable under DWC, particularly in BA soil. DNA-stable isotope probing (DNA-SIP) further identified active microbes, linking microbial and environmental drivers that regulating the allocation of C from FOM to different SOC pools.

Together, our results show that biochar mediates biotic and abiotic Fe–C coupling, reshaping the balance between microbial C turnover and SOC stabilization, and highlight both the capacity and the vulnerability of BA for soil C stabilization under future climate change.

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**Supporting Figure**



# Slope aspect regulates constrained soil organic carbon dynamics under long-term grazing exclusion in semiarid grasslands

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**ABSTRACT**

Grazing exclusion is widely used to increase soil organic carbon (SOC) in degraded grasslands, but whether SOC continues to accumulate under prolonged exclusion and how this process is shaped by slope aspect remain unclear. Here, we investigated SOC dynamics along a 41-year grazing exclusion chronosequence across contrasting slope aspects in semiarid grasslands. By partitioning SOC into particulate organic carbon (POC) and mineral-associated organic carbon (MAOC), we examined how plant inputs, nitrogen availability, and microbial processes regulate SOC dynamics. SOC exhibited a non-linear trajectory, increasing during the early (0 - 16 yr) to mid (16 - 33 yr) stages but declining during the late stage (33 - 41 yr) of grazing exclusion. Specifically, POC did not continue to accumulate under prolonged exclusion and became increasingly vulnerable to depletion, whereas MAOC was unable to fully compensate for this loss. Slope aspect strongly shaped the magnitude and pathways of SOC responses, the south-facing slope showed greater sensitivity to grazing exclusion, whereas the north-facing slope maintained relatively higher SOC. Overall, these findings demonstrate that the carbon sequestration potential of grazing exclusion is finite and strongly aspect-dependent, providing a mechanistic basis for optimizing exclusion duration and topography-sensitive carbon management in semiarid grasslands.

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# Divergent carbon stabilisation pathways in Australian soils

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**ABSTRACT**

The persistence of soil organic carbon (SOC) depends on its partitioning into mineral-associated (MAOC) and particulate (POC) fractions. Yet the combined roles of climate, mineralogy, and land use in shaping these fractions remain unresolved across continental gradients. Here, we analysed 249 Australian topsoils from 65 paired sites along a 550 mm rainfall isohyet. Samples were grouped into four climate–texture clusters (Subtropical Coarse, Subtropical Fine, Temperate Coarse, Temperate Fine) to disentangle the effects of thermal and hydrological regimes, soil properties, and land use on SOC fractions and saturation. Subtropical soils consistently exhibited high stabilisation efficiency (fMAOC ≈ 0.8) despite low SOC stocks, reflecting strong mineral–organic interactions under carbon-limited and water-stressed conditions. Temperate soils stored greater SOC stocks but frequently exceeded predicted MAOC capacity, indicating diminishing stabilisation efficiency. In subtropical fine soils, agriculture elevated fMAOC through microbial activity and nutrient inputs, yet this occurred alongside depleted SOC and POC, highlighting a trade-off between stabilisation efficiency and carbon stock depletion. Across all clusters, land use effects were evident but secondary to climate and mineral properties. These findings challenge assumptions that dryland soils are universally vulnerable, showing instead that subtropical soils stabilise carbon efficiently but in small amounts, while temperate soils store more carbon yet are prone to saturation and management-induced losses. Our climate–texture framework highlights region-specific management priorities: enhancing mineral–organic interactions in subtropical soils and protecting vulnerable carbon stocks in temperate systems.

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# Biologically driven short-term inorganic carbon changes in calcareous soils

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**ABSTRACT**

Both soil inorganic carbon (SIC) and organic carbon (SOC) are affected by agricultural management. However, the former has received much less attention than the latter when assessing their role in the global carbon cycle, mainly due to the widespread assumption that SIC dynamics proceed at a very slow rate. Nevertheless, growing evidence shows that agricultural practices (e.g., irrigation, amendments, fertilizers) can drive significant and rapid changes in SIC that have not been considered in global carbon budgets, and that could represent potential SIC management strategies.

Among the practices known to influence SIC dynamics are the exogenous supply of $Ca^{2+}$ (e.g., through enhanced weathering or gypsum [$CaSO_4 \cdot 2H_2O$] application) and the introduction of irrigation in drylands. We monitored the effects of these management practices by studying the processes affecting SIC at two scales. The first study compared similar gypsum-containing soils under different management systems—rainfed and irrigated (25 years)—where SOC, SIC, and gypsum contents were measured at two depths. The second consisted of greenhouse and phytotron experiments using several plant species grown in substrates with varying gypsum concentrations. *Thymus* sp., *Rosmarinus* sp., *Brassica napus*, and *Astragalus* sp. were cultivated in pots containing silty loam material (30% $CaCO_3$) mixed with gypsum at 0%, 5%, 50%, and 80%.

In addition to the aforementioned variables, root calcification (observed microscopically) and $Sr^{2+}/Ca^{2+}$ ratios of biogenic calcite were quantified to estimate the proportion of calcite derived from gypsum-$Ca^{2+}$.

Results from the field study revealed changes in SOC turnover compared with the rainfed area, along with an increase in $CaCO_3$ and a decrease in gypsum content. These trends are consistent with previous observations of sulfate and bicarbonate concentrations in irrigation and drainage waters from irrigated watersheds containing gypsum-rich soils.

Similar patterns were detected in the pot experiments, with higher carbonate and lower gypsum contents. Root calcifications were observed in all species, with *Brassica napus* showing the highest degree of root calcification. Increasing gypsum content in the substrate significantly enhanced carbonate formation in both the substrate and roots, confirming that gypsum supplies $Ca^{2+}$ for calcite precipitation, leading to net carbon sequestration. $Sr^{2+}/Ca^{2+}$ ratios of biogenic calcite allowed the use of mixing equations that confirmed this hypothesis, as the proportion of calcite derived from non-carbonate $Ca^{2+}$ increased with gypsum content, reaching about 60%.

Our results are promising, representing a first step toward designing management practices for both rainfed and irrigated systems that promote SIC sequestration—an approach that could be incorporated into future carbon credit schemes.

**Acknowledgments**

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# Carbon-Nitrogen Dynamics and Soil Aggregation in Terrace Soil of Rice-Wheat Cropping System

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## ABSTRACT

The sustainability of intensive rice–wheat systems in the Indo-Gangetic Plains is increasingly threatened by soil degradation *driven by organic matter depletion*, structural decline, and nutrient imbalance. This study aimed to evaluate the long-term effects of integrated nutrient management (INM) combining organic and inorganic inputs on soil carbon (C) and nitrogen (N) dynamics, physical properties, and biological activity in terrace soils of Bangladesh. This study assessed long-term effects of INM on soil carbon (C) and nitrogen (N) dynamics, physical properties, and biological activity in terrace soils of Bangladesh through a 32-year field experiment involving compost, cowdung, green manure, rice straw, and varied nitrogen (N) fertilizer rates. Compost application significantly enhanced soil total C and organic C stocks by 10%, microbial biomass C and N by 92% and 96%, respectively, and aggregate stability of 0.50 mm and 0.25 mm particles by 133% and 163%. Bulk density declined by 3%. C and N were concentrated in surface soils, decreasing with depth. Moderate N rates improved nutrient availability, whereas excessive N accelerated organic matter mineralization and reduced C stocks. INM practices consistently improved soil structure, biological activity, and nutrient retention, thereby strengthening climate resilience and productivity in sub-tropical systems. While C sequestration remained modest, continuous organic inputs are essential for sustaining soil fertility. Policy actions should promote organic fertilizers, farmer training on INM practices, and soil health improvement. Widespread adoption of INM offers actionable strategies for food security, soil restoration, and alignment with the UN Sustainable Development Goals.




**Fig. 1.** Policy recommendations for achieving the UN Sustainable Development Goals

**Keywords:** Soil fertility, organic materials, nitrogen fertilizer, carbon sequestration, wheat

# Soil C and N storages response to land-use and management changes: A comparison of various plant-soil ecosystems in Eastern Japan

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**ABSTRACT**

Soils could be carbon (C) sinks or sources depending on land use and management changes (LUMC) in different plant-soil ecosystems. Soil nitrogen (N) and its dynamics not only affect plant growth and crop production but also control soil C sequestration. Thus, C and N dynamics affected by LUMC in terrestrial ecosystems contribute not only to global and local environmental problems, including global warming, destruction of the ozone layer, acid rain, and eutrophication, but also to changes in soil fertility and crop production related to human sustainable development. This report examines how soil C and N storage respond to land-use and management changes, and presents a comparison of various plant–soil ecosystems in the Eastern Japan. In Japan, following the introduction of the rice acreage reduction policy, the conversion and abandonment of paddy fields have been increasing year by year. We found that even 40 years after paddy fields were converted into orchards or wetlands, the surface soil C content had not changed significantly. However, in areas converted into vegetation-free parking lots, the soil C content showed a marked decrease. In contrast, when sandy land was converted into vinyl-covered paddy fields, the soil C content increased more than fivefold after 50 years. In the coastal sand dune area, black pine plantation age significantly influenced soil organic C (SOC) and total N (TN) contents in the 0–50 cm depths of sandy soils. Moreover, over the past two centuries, SOC and TN stocks in the 0–50 cm soil depth have exhibited an asymptotic increase with black pine forest plantation age in the sand dunes. Five-year vegetation conversion from pasture to C3 and C4 plants affects dynamics of SOC and TN and their natural stable C and N isotopes via mediating C input and N leaching in same area. These results indicate that changes in soil C and N storage in response to LUMC are largely driven by vegetation type and biomass productivity in plant–soil ecosystems.

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# Cover crop quantity and quality jointly drive priming effects and new soil organic carbon formation across soil fertilization histories

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Cover cropping has gained significant attention from researchers and policy makers over the past decade as a promising strategy to increase soil organic carbon (SOC) stocks and mitigate climate change. However, the effects of cover crops on SOC often vary, with some studies reporting negligible or negative outcomes. Uncertainties remain regarding the environmental and management factors controlling carbon (C) inputs and subsequent SOC dynamics, particularly the role of soil nitrogen (N) availability in modulating C sequestration. We previously showed that the quantity of cover crop C was a key determinant of SOC formation in a sandy soil, both directly through new SOC formation and indirectly via priming of native SOC decomposition. The present study evaluates how quantity and quality of cover crop C inputs interact with long-term fertilizer management to influence SOC sequestration in a clayey loam soil.

Using soils from the Askov long-term experiment initiated in 1894 with contrasting fertilization histories (unfertilized = ZERO, mineral = NPK, and animal manure = AM), we performed a 4-month mesocosm study (20ºC) with two $^{14}$C-labelled cover crop residues differing in C/N ratio (ryegrass, C/N=60; red clover, C/N=16), applied at increasing doses (0, 0.1, 0.2, 0.3, and 1.5 mg C kg$^{-1}$ soil). We investigated whether fertilization history and N content of the cover crops affected the formation of new SOC from cover crop C inputs, and whether positive priming effects at low residue-C inputs, previously observed in sandy soil, also occurred in this clayey loam.

The results showed that net C losses induced by cover crop residues were 62-91% of the initially added C across treatments, with higher losses caused by ryegrass than red clover regardless of soil fertilization histories. Yet, isotopic partitioning also revealed greater ryegrass C retention in the soil except for at the highest C addition dose, indicating that the higher C loss in this treatment was primarily driven by stronger positive priming rather than lower stabilization efficiency. Indeed, ryegrass resulted in increasing positive priming effects with higher addition doses across fertilization history, while red clover only triggered weak positive priming effects in ZERO, but not in NPK and AM fertilized soils.

We therefore hypothesized that the positive priming effects induced by ryegrass were driven by microbial N mining arising from imbalanced C-N stoichiometry in ryegrass residue, whereas red clover mitigated excessive native SOC decomposition through more balanced C-N inputs. Ongoing analyses, including fungal and bacterial amplicon sequencing and extracellular enzyme assays, will further elucidate the microbial mechanisms underlying the effects of cover crop quantity and quality on SOC dynamics across fertilization histories.

**Key words:** Cover crops, SOC dynamics, litter quality, litter quantity, priming effects

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# Root exudates-mediated rhizosphere microbiome participate in carbon fixation along the chronosequence

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**ABSTRACT**

Orchard ecosystems play an important role in global carbon sequestration, but have not received sufficient attention. Therefore, tracking the changes of rhizosphere microbial community composition and root exudates of apple on the Loess Plateau, China and revealing their contribution to soil organic carbon (SOC), and its regulatory mechanism, can provide valuable information for carbon sequestration in orchard rhizosphere ecosystems. Our findings highlight that the accumulation of SOC in the rhizosphere of fruit trees mainly occurred in the period of decline rather than in the sapling stage and the full fruit stage. This is because during the growth and fruiting period of fruit trees, vigorous rhizosphere secretions lead to highly active and diverse microorganisms that consume SOC, with amino acids playing a key mediating role. However, in the decay stage, secretions decrease and SOC accumulation from microbial residue carbon, the contribution of fungal carbon is greater than that of bacterial carbon. Importantly, root exudates affect rhizosphere soil organic carbon rather than microorganisms by directly regulating rhizosphere soil physicochemical properties and soil enzyme activity.

**Key words:** Soil organic carbon, microbial necromass carbon, rhizosphere fungal diversity, rhizosphere bacterial diversity, root exudates, amino sugars, Loess Plateau

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# Chemical Composition of Soil Organic Carbon and Its Relationship with Soil Properties and Carbon Dynamics in Tropical Soils of Thailand

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## ABSTRACT

Soil organic carbon (SOC) in tropical regions is strongly influenced by high temperatures and abundant precipitation. These conditions create an environment that favors rapid organic matter decomposition, resulting in unique SOC dynamics that differ markedly from those in subtropical and temperate zones. Consequently, tropical soils often exhibit poor plant nutrition and relatively low SOC content. However, information on the chemical composition of SOC in tropical soils and on how this composition relates to soil characteristics and carbon dynamics, especially in Thailand, is still scarce. This study aims to examine the relationships among SOC chemical composition, soil properties, and SOC dynamics in agricultural tropical soils of Thailand. Surface soil samples were collected from a variety of crop fields. We employed three complementary approaches: (i) stable C ($\delta^{13}C$) and N ($\delta^{15}N$) isotope analysis with an isotope ratio mass spectrometer coupled to an elemental analyzer; (ii) density fractionation of SOC using sodium polytungstate; and (iii) solid-state $^{13}C$ nuclear magnetic resonance (NMR) spectroscopy to characterize SOC chemical composition. Our results demonstrated that tropical soil conditions promote rapid SOC decomposition. OC contents were low (6.3–19.1 g $kg^{-1}$), and soils were limited in nutrients and cation-exchange capacity (CEC). The $\delta^{13}C$ values indicated that the OC originated primarily from the existing vegetation. The $\delta^{15}N$ signatures suggested that nitrification was the dominant N-transformation process in most crops, whereas lower $\delta^{15}N$ values in paddy soils reflected denitrification under anaerobic conditions. Density fractionation showed that the high-density fraction (HF; 3.0–14.6 g OC $kg^{-1}$ soil) represented the largest and more stable SOC pool. The free low-density fraction (fLF; 1.0–2.5 g OC $kg^{-1}$ soil) and mineral-associated low-density fraction (mLF; 1.3–3.7 g OC $kg^{-1}$ soil) contained smaller OC amounts. Significant differences in $\delta^{13}C$ among sites were observed for fLF and mLF, but not for HF, indicating that SOC dynamics are mainly confined to the relatively labile fractions, while the more stable pool is comparatively less affected by cultivation across crop fields. The principal component analysis linked alkyl C and n-alkyl C with silt and clay content, CEC, and soil pH in tropical soils. In contrast, di-O-alkyl C and carbohydrate C, which represent labile, easily decomposable SOC, were positively associated with decomposition processes and were predominantly present in fLF and mLF. Carboxyl C and aromatic C, regarded as more stable forms of OC, were primarily found in HF. Overall, this study revealed the chemical composition of SOC and its connections to SOC dynamics and soil properties in Thailand's tropical agro-ecosystems. These findings provide a scientific basis for developing improved soil management strategies aimed at both enhancing crop productivity and increasing SOC stocks in tropical regions.

**Keywords:** soil organic carbon (SOC), SOC fractionation, stable C and N isotopes, SOC chemical composition, agricultural tropical soils

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# Synergistic Relationships Between Soil Organic and Inorganic Carbon in North China's Croplands: A Mini-review and Prospective

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## ABSTRACT

Soil organic carbon (SOC) and inorganic carbon (SIC) are critical components of terrestrial carbon pools, each playing distinct yet interconnected roles in soil health and the global carbon cycle. Although certain progress has been made in understanding the dynamics of SOC and SIC and their responses to farmland management practices in recent years, challenges remain due to incomplete theoretical frameworks and unclear practical pathways for elucidating SOC–SIC interactions. This mini-review synthesizes recent findings on the spatial distribution, transformation mechanisms, and mutual feedbacks between SOC and SIC in North China's croplands, where semiarid conditions and intensive agriculture create unique carbon cycling dynamics. Evidence suggests that organic amendments, irrigation regimes, and conservation tillage not only influence SOC accumulation but also alter SIC formation through shifts in soil pH, calcium availability, and microbial activity. Conversely, SIC—particularly pedogenic carbonates—can stabilize SOC by promoting aggregate formation and buffering soil acidity. We highlight key knowledge gaps, including the long-term stability of SOC–SIC linkages under climate change and the need for integrated monitoring approaches. Finally, we propose a prospective research agenda combining isotopic tracing, remote sensing, and machine learning to better quantify and manage SOC–SIC synergies for sustainable carbon sequestration in North China's agroecosystems.

**Keywords:** Soil organic carbon; Soil inorganic carbon; Synergistic relationships; Agricultural land.

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# Organic Amendments Enhance the Formation of both Organic and Inorganic Carbon in Macroaggregates of Cropland in the North China Plain

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## ABSTRACT

Soil organic carbon (SOC) and inorganic carbon (SIC) play critical roles in carbon sequestration and soil health; however, their distributions across soil aggregates under organic amendments remain insufficiently understood. We hypothesized that straw and biochar would promote the formation of macroaggregates, and enhance both SOC and SIC accumulation in macroaggregates. To test this hypothesis, we examined the effects of straw and biochar on aggregate structure, SOC and SIC distribution, and carbon conversion efficiency. Results showed that both amendments reduced the proportion of microaggregates and increased macroaggregate formation, with straw showing a slightly stronger effect. SOC increased under both amendments; the highest SOC content under straw occurred in the 1–0.5 mm fraction (7.3 g $kg^{-1}$), whereas the overall maximum was observed in the 2–1 mm fraction under high-rate biochar (9.4 g $kg^{-1}$). Biochar treatments resulted in larger newly formed SOC accumulation (1.3–3.5 g $kg^{-1}$) and greater conversion efficiency (52–62%) than straw treatment (0.8–1.3 g $kg^{-1}$, 22%). New SOC contributions were consistently highest in the 2–1 mm fraction, with the greatest contribution (36.5%) occurring under high-rate biochar. Relative to the control, both amendments increased SIC content in aggregates >0.5 mm, with biochar showing the greatest increase (3.5 g $kg^{-1}$). SIC distribution differed between amendments, peaking in the 1–0.5 mm fraction under straw but shifting to the 2–1 mm fraction under biochar. A strong positive correlation was observed between newly formed SOC and SIC in aggregates >0.5 mm, suggesting coupled stabilization of organic and inorganic carbon during aggregate formation. Overall, although straw more strongly promoted macroaggregate formation, biochar demonstrated greater potential for enhancing aggregate-associated carbon stabilization and increasing SOC and SIC sequestration in croplands of northern China.

**Keywords:** Soil organic carbon; Soil inorganic carbon, Soil aggregation; Biochar; Wheat straw

# Coupling mechanism of soil organic carbon and inorganic carbon

**ABSTRACT**

Soil inorganic carbon (SIC) in arid and semi-arid regions, especially pedogenic carbonates (PIC), plays a critical role in carbon sequestration and soil health, yet its coupling with soil organic carbon (SOC) fractions and microbial processes remains poorly understood. Here, we develop an integrated framework combining SOC fractions, nutrient status, microbial community structure and soil physicochemical properties to elucidate PIC accumulation patterns and the drivers of organic–inorganic carbon co-stabilization across different region–crop combinations. Field investigations were conducted in two typical cropping zones dominated by major crops in the arid region of Northwest China. Carbon fractions differed markedly among sites. Maize fields in Bole (B–M) had significantly higher PIC and SOC and were dominated by stable fractions, including mineral-associated organic carbon (MAOC) and heavy-fraction organic carbon (HFOC), along with enrichment of SIC, PIC and dissolved inorganic carbon (DIC). Cotton fields in Bole (B–C) were dominated by particulate organic carbon (POC) and lithogenic carbonates (LIC), whereas soils in Wuwei were dominated by labile SOC pools, i.e., dissolved organic carbon (DOC) and light-fraction organic carbon (LFOC). Correlation analyses showed that MAOC and HFOC were positively related to SIC, PIC and DIC, while DOC and LFOC were negatively related to SIC. Microbial diversity was tightly linked to carbon fractions, with fungal diversity more sensitive to coupled shifts in SOC and SIC, and bacterial communities more strongly regulated by inorganic carbon forms and pH. Microbial biomass carbon and nitrogen (MBC, MBN) were positively correlated with SOC, SIC and PIC but not with LIC, indicating greater reliance on pedogenic than lithogenic carbonates. Random forest and partial least-squares path modeling (PLS-PM) identified C:N ratio, cation exchange capacity (CEC), microbial status and MAOC as key mediators of PIC formation. The strong positive association between MAOC and SIC/PIC suggests that stable SOC may promote co-precipitation with carbonates and thus enhance organic–inorganic carbon stabilization. Our results verify a synergistic accumulation of organic and inorganic carbon fractions and highlight the bridging role of microbial diversity and nutrients in PIC formation. SOC and PIC form a positive feedback in dryland croplands, whereas labile carbon and SIC engage in competitive regulation. Coupling between microbial status and stable SOC fractions is a critical leverage point for enhancing carbon sequestration and soil health. These findings suggest that optimized irrigation, fertilization and crop configuration can strengthen the carbon sink function of arid farmlands.

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# Global response of soil organic carbon pools to land management and climate change

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## ABSTRACT

Soil organic carbon (SOC) is key to sustaining agricultural productivity and safeguarding ecosystem services amid daunting challenges from human activities and climate change. SOC embodies a continuum from coarse remnants of plant matter (particulate organic carbon, POC) to resilient mineral-associated organic carbon (MAOC), with each component responding uniquely to environmental factors, making assessment crucial. In our study, we compiled an extensive global dataset comprising 6,668 SOC data points, alongside 3,088 POC and MAOC observations. SOC accumulation is more closely associated with POC. POC shows stronger sensitivity to management and climate change than MAOC, indicating its potentially larger role in driving SOC dynamics under anthropogenic activities and climate change. Random Forest models unveil the strong influence of soil type on the spatial distribution and relative proportions of SOC pools, highlighting its pivotal role in shaping soil carbon composition. Our projections draw a sobering picture: mounting climate pressures lead to troubling decline in global SOC concentration. From 2060 to 2080, SOC loss under various climate scenarios is estimated to reach 0.7-1.2 times the $CO_2$ emissions from anthropogenic sources recorded in 2023 (40.9 Pg). These findings emphasize the urgent need to safeguard carbon reservoirs from the threats of human impact and climate change.

**Keywords:** soil organic carbon, particulate organic carbon, mineral-associated organic carbon, climate change, land use change

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# The conversion of paddy to upland soils triggers the loss of soil organic carbon stocks by promoting Fe oxide crystallization

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## ABSTRACT

The variations in SOC stock can substantially alter global carbon cycling, with potential to drive significant fluctuations in atmospheric carbon concentrations. Intensive land use changes and agricultural practices—particularly cropping system intensification, tillage operations, and erosional processes—have collectively driven massive carbon losses (40-133 Pg C) from global cropland soils over recent centuries. Although paddy fields account for less than 9% of global cropland area, they store a significant proportion of the global agricultural soil carbon pool (exceeding 14%), playing a pivotal role in the global carbon cycle. In southern China, paddy fields have been converted to upland crop cultivation to alleviate heavy metal pollution and water resource constraints. The organic carbon content in paddy soils exhibit 1.5–1.8 times higher than that of upland soils due to greater inputs of crop roots and litter-derived carbon, slower decomposition rates of organic carbon under anaerobic conditions and the critical role of Fe oxides in stabilizing organic carbon. Additionally, soil pH significantly regulates organic carbon storage in paddy soil systems. The conversion of paddy to upland soils disrupting key biogeochemical processes that regulate SOC cycling. Therefore, understanding these changes is of great significance for managing soil carbon sequestration mechanisms.

SOC can be divided into two primary fractions: mineral-associated organic carbon (MAOC) and particulate organic carbon (POC). Mineral-associated organic carbon (MAOC) plays a critical role in SOC stabilization through both chemical bonding with mineral particles and physical encapsulation within soil aggregates. Research findings indicate that the recalcitrant organic carbon pool, rather than labile organic carbon pools, constitutes the core mechanism governing paddy soil carbon sequestration function. Significant alterations in redox conditions caused by land use changes in rice paddies, particularly through fluctuations in soil moisture regimes, should markedly modulate the stability and transformation of OC-Fe complexes. The impact of conversion of paddy to upland soils on SOC components requires further investigation. The newly recognized ‘iron gate’ mechanism suggests that phenol oxidative activity is mainly controlled by Fe(II) and decreases with water-level decline. This leads to the accumulation of dissolvable aromatics and a reduced activity of hydrolytic enzymes, thereby enhancing SOC preservation. Knowledge of the interaction of Fe oxide with phenol oxidative and hydrolytic enzyme activity when conversion of paddy to upland soils may contribute to our general understanding of SOC stabilization.

Despite the growing understanding of above processes, the specific mechanisms underlying the changes in SOC stocks during the conversion of paddy to upland soils remain poorly understood. In particular, the roles of Fe oxides, soil enzyme activities, and Fe-oxidizing and reducing bacteria composition in this process require further investigation. The objective of the present study was to improve our understanding of the impact of paddy soil land use change on SOC stocks and the underlying factors regulating its persistence. To achieve this, the experiment of converting paddy to upland fields was designed. The aims of the present study were to (1) investigate the reasons of the SOC loss caused by paddy conversion to upland soils, and (2) to explore the mechanisms of Fe oxides in soil organic carbon stock under the conversion from paddy to upland soils. It was hypothesized that: (1) the conversion of paddy to upland soils led the SOC loss, and (2) this conversion would lead to the continuous aging and crystallization of Fe oxides, weakening the binding ability of Fe oxides with organic carbon and the 'iron gate' mechanism, resulting in a decline in SOC.

To address this, long-term rice cultivated fields were partitioned: i) converted to maize-maize (MM) cropping system, and ii) maintained rice-rice (RR) cropping system. Each cropping system included: control (CK), nitrogen, phosphorus and potassium fertilizers (NPK), and NPK combined with straw incorporation (NPKS). The seasonal dynamics of SOC stocks, Fe oxide forms, Fe-bound organic carbon stocks, related enzyme and soil properties have been continuously monitored. Results showed that SOC stocks in the MM cropping system decreased by 9-22% compared with the RR cropping system. The decrease of MAOC (16%) in SOC fractions was significantly higher than that of POC (7%), primarily attributed to the decline of the stocks of complexed ($Fe_{PP}$) (9%–10%), amorphous ($Fe_{HH}$) (9%–31%) Fe oxides, as well as their associated organic carbon stock ($Fe_{PP}$-OC: 5%–15% and $Fe_{HH}$-OC: 14%–33%) after the conversion of paddy to upland soils. After the conversion of paddy to upland soils, the absolute abundance of Fe redox bacteria significantly decreased, with the absolute abundance of Fe-reducing bacteria (FeRB) being substantially higher than that of Fe-oxidizing bacteria (FeOB). The dominant species of FeRB included *Anaeromyxobacter*, *Desulfobacca*, *Syntrophobacter*, and *Syntrophorhabdus*, while the dominant species of FeOB included *Leptothrix*, *Gallionella*, and *Rhodomicrobium*. Specifically, changes in FeRB further influenced Fe(II) levels, thereby driving transformations in Fe oxide forms and their associated Fe-bound OC content. After paddy conversion to upland soils, the ‘iron gate’ mechanism in protecting SOC loss was weakened due to the crystallization and aging of Fe oxide. In addition, increased activity of hydrolase further increased the loss of SOC. According to random forest (RF) model, the DOC, $Fe_{HH}$, $Fe_{HH}$-OC and $Fe_{DH}$ were found to be the most important variables for predicting the SOC, MAOC, POC. Moreover, correlation analysis illustrated that SOC, POC, MAOC gradually decreased with decreasing DOC, $Fe_{HH}$ and $Fe_{HH}$-OC. These findings indicated that the conversion of paddy to upland soils negative impacts SOC stocks by weakening the association between Fe oxides and SOC, underscoring the pivotal role of Fe oxides in SOC loss under paddy land use change.

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# Management's Role in Loss of Color and Organic Carbon in Great Plain Soils of the United States

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**ABSTRACT**

Loss of carbon is an important issue that scientists have been trying to address since modern farming techniques became standard. Especially in the central Great Plains of the United States, the 1930's Dust Bowl is a recent catastrophe, but we are still suffering from a century of overworked soil. In the field, color can give us an insight into the nutrient dynamics that are going on in the soil, especially carbon/organic matter. Soil color is traditionally described using the Munsell soil color system with hue, value, and chroma.

During the study period 150 fields varying in management from native grassland, restored grassland, conservation farming, and conventional farming systems were sampled in Kansas. Two pedons were collected per field, for a total of 300 pedons sampled between 2022 and 2024 across Kansas. Soil profile descriptions were completed, and soil samples were collected for the 0-5, 5-10, 10 to the remainder of the A horizon, and by genetic soil horizon thereafter to a depth of 1 m. Bulk density, soil organic C (SOC), water stable aggregation, and particle size were analyzed for each sample.

During the field soil description, the Capsure Munsell Soil Color device was used to measure the moist soil color. In the Munsell system soil is described in hue, value, and chroma. The field descriptions have shown a lighter color value in the top of the A (0 to 5 cm) vs the bottom portion of the A horizon (10-15 cm) that wouldn't be explained by erosion, parent material or difference in mineral soil alone. This was most noticeable in the conservation-ag focused systems which have been no-tilled for 10-30 years at the time of sampling. This was mostly observed in no-till and some conventionally tilled fields. Mixing during tillage may be hiding some of this organic matter and color loss in conventional tillage systems.

However, root depth also matches up well with this loss of color in the top 10 centimeters and can show the role of our cropping systems in deteriorating carbon stores in the topsoil. Comparing how color chip differences appear among differences in cropping system, tillage, and texture can help to explore where carbon loss is happening in our soils.

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# Nitrification-induced acidity controls $CO_2$ emission from soil carbonates

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## ABSTRACT

Nitrification acidifies soil, and the produced $H^+$ are neutralized by inorganic carbon (C) in soil leading to irreversible $CO_2$ emissions. $CO_2$ released by nitrogen (N) fertilizer-induced acidification is partitioned between solid ($CaCO_3$ re-precipitation), liquid (dissolved $HCO_3^-$ and $CO_3^{2-}$) and gaseous ($CO_2$) phases. Therefore, quantifying the effects of N fertilization on $CO_2$ emissions from soil inorganic C is an enormous challenge. $^{14}C$-labeled $CaCO_3$ was used as a model inorganic C to trace the released $CO_2$ caused by acidification by five fertilizers: chicken manure, urea, $KNO_3$, $NH_4NO_3$, and $(NH_4)_2SO_4$ added at three N rates. Cropland soil was homogenously mixed with $Ca^{14}CO_3$ powder and fertilizers, and the emitted $CO_2$ was trapped in NaOH solution to determine total $CO_2$ and $^{14}CO_2$ efflux originated from inorganic C. Fertilization, particularly ammonium-based fertilizers ($(NH_4)_2SO_4$, $NH_4NO_3$), strongly decreased soil pH by 0.35 units over 40 days. All fertilizers except $KNO_3$ increased total $CO_2$ emissions by 21%-490% compared to the unfertilized control soil. The fertilization effects on cumulative $^{14}CO_2$ emission induced by $CaCO_3$ neutralization, corresponded to acidification and decreased in the order $(NH_4)_2SO_4$ > $NH_4NO_3$ > urea > $KNO_3$ > chicken manure. Ammonium-based fertilizers induced the strongest $CO_2$ emissions originated from inorganic C, emitting 1.6-4.5 times more $^{14}CO_2$ than non-fertilized soils during the first nine days. The total $CO_2$ emissions from SIC were proportional to the fertilizer dose applied. Therefore, we conclude that both the choice of N fertilizers and their application rates need to be considered to control $CO_2$ emissions originated from inorganic C. The soil inorganic C losses should be prevented not only because of their irreversible contribution to atmospheric $CO_2$, but also to safeguard ecosystem services of $CaCO_3$, such as organic matter preservation, soil structure stabilization, and C sequestration.

# The Impact of Soil Heterogeneity on Organic Carbon Mineralization

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**ABSTRACT**

Soil heterogeneity significantly influences the dynamics of organic carbon mineralization and carbon sequestration effects. To investigate the impact of soil heterogeneity on organic carbon mineralization and its underlying mechanisms in subtropical paddy soil, a laboratory-scale experiment was conducted. The paddy soil was stratified horizontally, and equal amounts of glucose were applied to different layers to create gradients of spatial heterogeneity in soil organic carbon (high heterogeneity, low heterogeneity, homogeneous, and no-carbon control). Diffusion and isolation treatments were set up using different layered materials to monitor the characteristics of organic carbon mineralization and changes in environmental factors. The effects of spatial heterogeneity in organic carbon distribution on mineralization were analyzed. The results showed that both the rate and cumulative amount of organic carbon mineralization decreased with increasing heterogeneity. The homogeneous treatment exhibited the highest mineralization rate, while differences between treatments under diffusion conditions were smaller than under isolation conditions. Diffusion effect on cumulative mineralization in the high-heterogeneity treatment was stronger than other treatments. Regardless of substrate diffusion, the dissolved organic carbon (DOC) and microbial biomass carbon (MBC) contents in layers with added substrate were significantly higher than in layers without substrate, while ammonium nitrogen ($NH_4^+$-N) content was lower. Under diffusion conditions, average DOC content of layers increased, while average MBC, $NH_4^+$-N, and nitrate nitrogen ($NO_3^-$-N) contents decreased. This study demonstrates that soil spatial heterogeneity influences organic carbon mineralization by altering substrate distribution and microbial microenvironments.

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# Global warming potential in rice paddy soil applied with different fertilization and tillage management

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## ABSTRACT

Previous studies on greenhouse gas emissions from paddy soils have often addressed tillage and organic amendments as independent factors. In this study, eight treatment combinations integrating till and no-till systems with four fertilization types including chemical fertilizer (NPK), NPK+composted manure (CM), NPK+green manure (GM), and NPK+CM+GM were installed. The objective of this study was to evaluate the effect of different fertilizations and tillage managements on greenhouse gas (GHG) emissions, net ecosystem carbon budget (NECB), net global warming potential (net GWP), and greenhouse gas intensity (GHGI) in rice paddy soil. Field experiment (2024–2025) was conducted at the Experiment Farm of Pusan National University in Miryang, Republic of Korea, using rice plant (*Oryza sativa* L.) as the cultivated crop. Total carbon (C) input was greatest with NPK+CM+GM (676 kg ha$^{-1}$), followed by NPK+CM (549 kg ha$^{-1}$), NPK+GM (248 kg ha$^{-1}$), and NPK (41.7 kg ha$^{-1}$). Total nitrogen (N) input was also greatest with NPK+CM+GM (121 kg ha$^{-1}$), followed by NPK+GM (105 kg ha$^{-1}$), NPK+CM (93.1 kg ha$^{-1}$), and NPK (91.4 kg ha$^{-1}$), reflecting the increasing contribution of organic amendments. Carbon dioxide ($CO_2$) emissions were approximately twice higher under till than no-till. In the comparison between NPK and NPK+CM, $CO_2$ emissions with NPK was higher than NPK+CM, implying that total C input did not affect $CO_2$ emissions. Mean value of methane ($CH_4$) emissions across fertilizations were about 20% higher with the no till than till. The trend of $CH_4$ emissions was similar to that of total C input, increasing with higher C input. Nitrous oxide ($N_2O$) emissions increased with increasing total N input. Nitrous oxide emission was the greatest with NPK+CM+GM and followed by NPK+GM, NPK+CM and NPK. The NPK+CM+GM showed the greatest NECB (13.0 Mg ha$^{-1}$), suggesting considerable C sequestration potential. The trend of NECB was similar to that of total C inputs, meaning that high C inputs may lead more C sequestration. Mean value of rice grain yield across all fertilizations was significantly higher under the till system than the no-till system. In both till and no-till, total biomass yields were not significantly different among all treatments, but the mean value of total biomass across fertilizations slightly higher with till than no-till. NPK+CM+GM had the highest value of net GWP but the lowest value of GHGI. In no-till, the values of net GWP and GHGI with NPK, NPK+CM and NPK+GM were similar. In till, net GWP increased from -5.49 to -4.54 and to -4.15 with from NPK to NPK+CM and to NPK+GM, respectively. However, the trend of GHGI was opposite to that of net GWP. A higher value of net GWP suggested a greater overall contribution to global warming. Even though NPK+CM+GM had the greatest NECB, it exhibited the greatest net GWP due to its large greenhouse gas emissions. However, the lower GHGI value with this treatment reflected that its grain yield was substantial enough to offset its higher net GWP.

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# Soil Carbon-Nitrogen Pools in Different Land Use Types and Varying Time Scales: Implications for Soil Health and Sustainable Agriculture

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**ABSTRACT**

This study critically examines the comparative effects of various land use types and the duration of no-till practices on soil carbon (C) and nitrogen (N) pools, along with a range of soil health indicators on an Oxic Paleustalf (Ferric Luvisol) within a moist lowland forest ecology. Given the escalating concerns over soil degradation and the urgent need for sustainable agricultural practices, this research emphasises the importance of understanding how different agricultural methods impact soil health in Nigeria and other similar pedoclimatic regions. The study evaluates the influence of conventional tillage, no-till farming, and natural forest ecosystems on vital soil properties. Apart from the various soil and carbon fractions, key indicators such as bulk density, pH, aggregate stability, moisture retention, leaching potential, and nutrient holding capacity were assessed to determine the extent of soil health improvements resulting from notill practice over varying time scales. The findings reveal that while notill practices markedly enhance soil C and N pools, the duration of these practices is critical in manifesting significant impacts on soil health. Notably, the study highlights the potential of notill agriculture to restore soil functions comparable to those of undisturbed ecosystems; however, it also underscores the limitations associated with shorter adoption periods. This research provides valuable insights for agronomists and land managers in mesic forest and savanna ecologies, aiming to develop effective strategies that enhance soil health and agricultural sustainability. Ultimately, the study advocates for tailored land management approaches that not only conserve soil health but also promote resilience in agricultural systems amidst changing environmental conditions.

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# Soil Acidification in the Anthropocene

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**ABSTRACT**

Soil acidification is a global problem raising in the last decades mainly because of intensive nitrogen (N) fertilization of croplands and high atmospheric N deposition. The most natural acidification processes are boosted by human induced acceleration of biogeochemical cycles of nutrients and ballast elements, leading to irreversible losses of base cations from soils by leaching and removal with harvest, and to $CO_2$ fluxes into the atmosphere.

In this talk, we will raise the awareness of soil acidification processes mainly related to N fertilization in intensive agriculture. Acidification mechanisms and soil buffering systems will be shortly presented. As rhizosphere is one of the most important hotspots of soil acidification, the processes at root surface and the root-microbial interactions leading to $H^+$ release will be visualized and discussed. Despite microscale of rhizosphere acidification processes, and field scale of N fertilization, the consequences are of global importance. The losses of soil inorganic C (SIC) – mainly $CaCO_3$ – as $HCO_3^-$ leaching and as $CO_2$ release from calcareous soils amount for 7.5 Tg C $yr^{-1}$. Lime application to remediate soil acidity is another direct source of $CO_2$ emission and amounts for 273 Tg C $yr^{-1}$ as $CO_2$ release.

In contrast to C losses as $CO_2$ by soil organic matter by decomposition, the $CO_2$ release by $CaCO_3$ neutralization including lime application are unidirectional and irrecoverable: it is impossible to bring the released $CO_2$ back into soil as $CaCO_3$. Functions of SIC for plant nutrition, soil fertility and agroecosystem stability will be presented. Consequences of SIC depletion and strategies to remediate and control soil acidification will be discussed. Compared to SOC, wherein C stocks can be increased through management and organic fertilizer input, the SIC losses are irreversible and cause significant decline in soil health, ecosystem services, and functions. Concluding, N fertilization induced soil acidification and $CO_2$ losses from inorganic C are major C loss pathways, which jeopardize global efforts to mitigate climate change through SOC sequestration and dramatically decrease soil fertility.

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# Impact of Land Use and Windbreak Establishment on Soil Carbon Pools in Dryland Agroecosystems

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**ABSTRACT**

This study evaluates the impacts of long-term land use - specifically arable agriculture, livestock grazing, and afforestation with windbreaks established in the 1960s - on soil organic carbon (SOC) stocks and prospective carbon sequestration in the Shiraki Plain, Dedoplistskaro Municipality. Soil samples were collected across different land uses and analysed to quantify key soil fertility parameters and to evaluate their correlation with SOC content. The findings demonstrate distinct variability in SOC stocks across land use types. Soils beneath windbreaks, undisturbed for over sixty years, had the highest organic carbon, likely attributable to continual organic matter input via leaf litter and minimal anthropogenic disturbance. Pasture soils exhibited intermediate SOC concentrations, driven by persistent rhizodeposition and reduced mechanical perturbation. Conversely, cultivated soils subjected to frequent tillage and removal or burning of crop residues displayed substantially diminished SOC, reinforcing the hypothesis that improper soil management accelerates long-term soil carbon depletion.

Soils across all land-use types were alkaline and had high carbonate content. They also had high potassium levels but low nitrogen and phosphorus levels. The high concentration of carbonates probably limits the amount of phosphorus available by causing it to precipitate or become fixed in forms that plants cannot readily use. This reduction in available phosphorus can reduce plant growth, which in turn can affect how much carbon remains stored in the soil. The soils were mainly medium- to heavy-clay. They had a high cation-exchange capacity, which helps protect soil carbon by forming stable organomineral bonds.

The results show that windbreak belts are important for carbon storage because they help sequester carbon in the soil. They also provide ecological benefits, such as reducing wind erosion and maintaining soil moisture. Actions such as improving damaged windbreaks, reducing residue burning, maintaining ground cover, and adopting conservation tillage can increase SOC storage on the region's dryland farms by enhancing soil organic matter

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# Effects of alley cover crops on soil carbon and nitrogen along the soil profile in almond orchards under a Mediterranean climate

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## ABSTRACT

Intensification of Mediterranean orchards often accelerates soil degradation and threatens long-term productivity. Alley cover crops are promoted as a climate-smart practice, yet their influence on carbon (C) and nitrogen (N) distribution with depth is still poorly quantified (Montanaro et al., 2017). We assessed the effect of alley cover cropping on soil organic carbon (SOC) and total nitrogen (TN) in 0-1 m depth in six commercial almond orchards in Central Spain: three farms with alley cover crops established for 7 years (CC) and three farms with bare soil managed by tillage and herbicides (BS). In each orchard, six soil profiles (0-100 cm) were opened and four horizons (0 - 10, 10 - 40, 40 - 80, 80 - 100 cm) were identified and sampled. Bulk density, SOC, TN and their stocks were determined, together with cover-crop biomass (biomass) and its C and N inputs (CC_TC, CC_TN). In the surface horizon, SOC contents were very similar under both treatments (10.5 - 10.6 g $kg^{-1}$), with SOC stocks of 11.7 Mg $ha^{-1}$ (CC) and 12.1 Mg $ha^{-1}$ (BS). In contrast, SOC was higher under CC at 10 - 40 cm and 40- 80 cm horizons: 2.34-4.85 g $kg^{-1}$ in BS and 4.83-5.77 g $kg^{-1}$ in CC. SOC stocks ranged 11.89-21.79 Mg $ha^{-1}$ in CC and 17.67-28.07 Mg $ha^{-1}$ in BS. Although SOC at 80-100 cm was higher in BS (6.12 g $kg^{-1}$) than in CC (2.44 g $kg^{-1}$), total SOC stocks in the 0 - 100 cm profile reached 66.5 Mg C $ha^{-1}$ under CC compared with 49.4 Mg C $ha^{-1}$ under BS, a net increase of about 35 %. TN stocks were higher in BS than in CC (5.7 Mg $ha^{-1}$ and 7.8 Mg $ha^{-1}$ in CC and BS, respectively) due to a higher TN stock in horizon 2 of BS, with no significant differences in the other horizons between treatments. Biomass, CC_TC and CC_TN were significantly and positively correlated with SOC ($r = 0.4\text{-}0.5$; $P < 0.001$). These relationships indicate that orchards receiving larger inputs of cover-crop biomass as litter and root exudates, and associated C and N, are related to SOC and TN accumulation and storage > 10 cm depth. Overall, alley cover crops in almond orchards enhanced subsurface C storage and reshaped C-N profiles, highlighting the need to include deeper horizons when quantifying the mitigation potential of perennial cropping systems.

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# Linking the Chemical Composition of Soil Organic Carbon with the Formation, Stability, and Carbon Accumulation of Soil Aggregates under Divergent Land Uses

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## ABSTRACT

Understanding how land use practices influence soil organic carbon (SOC) chemistry and its interactions with soil aggregation processes is essential for predicting soil structural development and C sequestration potential. Nevertheless, the mechanisms linking SOC chemical composition to soil aggregation processes, aggregate stability, and aggregate-associated C under contrasting land uses remain insufficiently understood. Herein, we aimed to disentangle the relationships between SOC chemical composition and aggregate formation, aggregate stability, and aggregate-associated C under contrasting land uses. To achieve this goal, soil samples (0–20 cm) were collected from sites with comparable pedogenesis, general soil characteristics, and soil classification (Typic Haplustalfs) across seven land uses: forest (FR), pasture (PT), corn plantation (CO), sugarcane plantation (SC), cassava plantation (CA), orchard (OR), and abandoned land (AD). All soil samples were fractionated into five aggregate-size classes (>2000, 500–2000, 250–500, 53–250, and <53 μm) using a wet-sieving procedure. Soil aggregate stability was evaluated by calculating the mean weight diameter (MWD) and geometric mean diameter (GMD). All separated aggregate fractions were analyzed for their C content using a CHN determinator. The chemical composition of SOC was characterized using solid-state $^{13}C$ nuclear magnetic resonance (NMR) spectroscopy. Among the contrasting land uses, the macroaggregate (>2000 μm), 0.05–0.70 g $g^{-1}$, was significantly greater in PT soil, whereas the <53 μm fraction, 0.04–0.12 g $g^{-1}$, was significantly greater in CA soil, compared to the other land uses ($P < 0.05$). The MWD and GMD, ranging from 0.50–3.64 and 0.47–1.35 mm, respectively, were significantly higher in PT soil ($P < 0.05$). The amount of SOC stored in the >2000 μm fraction (0.96–13.34 mg C $g^{-1}$) was significantly higher in the PT soil, whereas that in the <53 μm fraction (0.55–1.90 mg C $g^{-1}$) was significantly higher in the CA soil ($P < 0.05$). Correlation analysis showed that the methoxy C % was positively correlated with the proportion of >2000 μm fraction, whereas the aromatic C-O % was positively correlated with the proportion of <53 μm fraction ($P < 0.05$). The MWD and GMD were positively correlated with the alkyl C % ($P < 0.01$) and methoxy C % ($P < 0.05$) and negatively correlated with aromatic C % ($P < 0.05$). The *O*-alkyl C %, including methoxy C % or carbohydrate C %, was positively correlated with SOC accumulation in the >2000 and 500–2000 μm fractions, while the aromatic C-O % was positively correlated with SOC accumulation in the <53 μm fraction ($P < 0.05$). Overall, the findings highlight that methoxy C % or carbohydrate C % may be considered key chemical components for promoting the formation and SOC accrual of macroaggregates under divergent land uses. Moreover, alkyl C % and methoxy C % are presumably desirable chemical components contributing to soil aggregate stability.

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# Soil carbon stocks and sequestration rates in Northern Irish grasslands

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**ABSTRACT**

It is estimated that global grasslands store 236 giga tons of carbon (C) in soil belowground, playing an important role in global climate change mitigation. Maximising soil carbon (C) stocks and sequestration in grasslands is crucial for climate change mitigation in Northern Ireland (NI), as grasslands cover ~95% of farmlands in NI. As part of Soil Nutrient Health Scheme, the most comprehensive regional soil nutrient sampling programme undertaken in the world, we aim to understand the environmental and management factors influencing C storage and sequestration in Northern Irish grasslands. Soil C and nitrogen (N) stocks were measured to a depth of 30 cm across 257 fields that were also surveyed in 2004. We found significant increase in soil C ($p$=0.0005) and nitrogen (p=0.0001) stocks over the last two decades, indicating sequestration. Field topography ($p$=0.0089) and depth ($p$ <0.0001) were significant predictors ofC stocks, while soil type had no impact. Flat fields stored more C (63.68 Mg C/ha) than undulating fields (54.66 Mg C/ha). We also found that adjacent hedgerow soils have significantly greater C and N stocks than the paired field soils, which is more pronounced in the deeper layers. Relative topography of hedgerows to the fields also significantly influenced C and N stocks, with hedgerows that were in lower altitude than fields showed greater soil N stocks, and hedgerows that were at the same altitude level as fields showing greater C stocks than field soils, while other relative topography classifications showed minimal variations. Soil sampling to full depth (up to 1m) is ongoing in these fields. Preliminary results from 162 sites indicate reduction in C stocks with depth: 0–15 cm (62.18), 15–30 cm (41.67), 30–45 cm (38.44), >45 cm (21.01 Mg C/ha), with 64% of soil C stored in the top 30 cm. Using field metadata and soil biogeochemistry data, we are applying modelling approaches to identify ideal management strategies for maximum C sequestration in NI grasslands.

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# A Large Carbon Stock in Global Coarse Woody Debris and Its Contribution to Soil Carbon Dynamics

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**ABSTRACT**

The global carbon budget framework is critical for formulating effective climate change mitigation strategies. As an important component of the soil carbon pool, coarse woody debris (CWD) stores approximately 8% of global forest carbon. However, its stock dynamics remain poorly understood within the global carbon budget, which could lead to substantial biases in estimating terrestrial carbon sink capacity and future carbon dynamics. To address this knowledge gap, we developed a global box-model framework to simulate CWD carbon stock dynamics, accounting for carbon inputs from aboveground vegetation mortality and outputs from decomposition. Notably, existing studies whether data-driven approaches or Dynamic Global Vegetation Models (DGVMs) have mainly treated CWD decomposition rate as a constant. Yet decomposition rates show pronounced global heterogeneity driven by environmental conditions, climate, wood traits, and biotic processes. Therefore, we compiled 2,477 observations of CWD decomposition rates from the literature and vegetation trait datasets and established a machine learning model to predict the global pattern of CWD decomposition rates. This model incorporates multidimensional drivers, including environmental factors, climate, wood traits, forest attributes, and biotic effects. Our work aims to provide a more accurate estimate of global CWD carbon stock dynamics, thereby offering essential scientific evidence to refine the global carbon budget and enhance the predictive capacity of terrestrial carbon cycle models.

**Keywords:** Coarse woody debris; Carbon budget; Carbon decomposition

# Soil Calcium Carbonate Leaching Process of Millennial Soil Chronosequence in Coastal Regions

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**ABSTRACT**

The soil carbon pool, as the largest carbon reservoir in terrestrial ecosystems, holds approximately twice the carbon stored in the atmospheric carbon pool and two to three times that of the vegetation carbon pool (Zhao et al., 2018). Soil inorganic carbon constitutes a vital component of the soil carbon pool. SIC represents mineral carbon formed during soil weathering, composed of primary and secondary carbonates. Calcium carbonate ($CaCO_3$), as the primary constituent of soil carbonates, significantly influences soil physical structure, chemical properties, carbon sequestration processes, acid-base equilibrium, and productivity (Ding et al., 2025), holding substantial scientific significance in soil environmental research.

A soil chronosequence refers to a set of soils of different ages originating from the same or similar parent material and formed under comparable environmental conditions (Chen et al., 2011). It connects the evolutionary history of soils and translates spatial differences between soils into temporal variations, thereby reflecting the rate and direction of soil formation changes (JIAO et al., 2020). Consequently, establishing soil chronosequence can be used to simulate the processes and rates of SIC leaching.

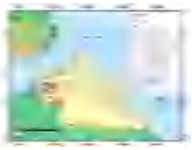


*Figure 3 Location Map of the Study Area Showing Dike Construction Periods and Soil Profile Sampling Sites in Cixi*

*Table 1 Table of Profile IDs versus Pedogenic Ages*

| Profile | CX00 | CX01 | CX02 | CX03 | CX04 | CX05 | CX06 | CX07 | CX08 |
|---|---|---|---|---|---|---|---|---|---|
| Soil age | 1100 a | 950 a | 550 a | 350 a | 280 a | 200 a | 170 a | 120 a | 60 a |

This study focused on soil calcium carbonate in coastal regions. By establishing a millennial soil chronosequence, we determined the calcium carbonate reserves at different soil depths and formation ages to investigate the spatio-temporal variation of soil inorganic carbon in coastal areas. Results indicate: (1) SIC Stock are high in the deep soil layer (60~100 cm) and low in the surface layer (0~20 cm).

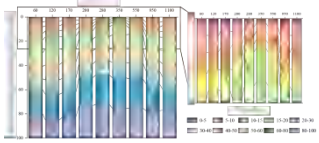


*Figure 4 Percentage of SICs at Each Soil Layer Depth Interval*

(2) According to the function fitting results, the exponential function is the best-fit model for describing the relationship between soil inorganic carbon Stock (SICs) and soil age. SICs exhibit a decreasing trend with increasing soil age.

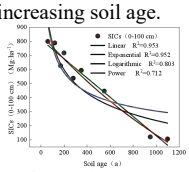



*Figure 5 Model fitting of SICs (0-100 cm) against pedogenic age*

Leaching-driven translocation of SIC to deeper layers is a primary mechanism for its depletion over pedogenic time.

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# Biochar-loaded NH+ 4-N effectively reduces carbon emissions by changing the composition of soil organic carbon and microbial community

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**Graphical ABSTRACT**



## Highlights

180 days of laboratory culture experiment revealed the effects of biochar supported ammonia nitrogen on organic carbon composition and microbial composition.
Ammonia nitrogen supported by biochar reduces soil carbon emission and improves the stability of soil organic carbon.
Biochar supported ammonia nitrogen is a new type of nitrogen fertilizer that can effectively reduce carbon emissions.

## ABSTRACT

Soil organic carbon (SOC) can influence soil carbon emissions and organic carbon (SOC) composition, with soil microorganisms playing an important role. However, the effects of biochar-loaded NH+ 4-N (BN) form on soil carbon emissions and its regulation of changes in soil SOC fractions remain unclear. As a result, a 180-day incubation study was performed utilizing three distinct types of nitrogen inputs: a single application of chemical nitrogen fertilizer (CF), a combination of biochar and chemical nitrogen fertilizer (BF), and biochar-loaded nitrogen (BN). Our results showed that compared to the CF (CK), BF addition increased soil carbon emissions (3.79), while the addition of BN reduced soil carbon emissions (2.26). BN decreased the C-mineralization of recalcitrant and labile C pools. Moreover, BN effectively enhanced the relative stability of soil dissolved carbon. By comparing the functional genes of microorganisms involved in carbon degradation, it was found that S-β-XYS and S-β-GC enzyme activities and gene expression varied significantly. Compared to CF, the activity of S-GC was significantly elevated in both BF and BN treatments at the 180-day. Furthermore, the activity of S-XYS was highest in BN at the 180-day compared to the remaining three treatments. Both S-β-XYS and S-β-GC enzymes regulate this SOC turnover in response to nitrogen input forms. BN considerably enhanced the relative prevalence of Sphingomonas and facilitated the decomposition and utilization of aromatic carbon, thereby influencing the stability of SOC. Overall, BN altered the fractions of SOC composition by modifying microbial community structure and enhancing carbon degrading enzyme activities, thereby reducing carbon emissions in soil environments.
Keywords: Biochar-loaded NH+ 4-N; Nitrogen input forms; Enzymatic activity; Microbial community

## 1 Introduction

Global climate change, driven by the greenhouse effect resulting from rising CO2 concentrations, has significantly impacted ecosystems worldwide, altering the carbon (C) cycle in terrestrial ecosystems (Reich et al. 2020). The soil carbon pool is the largest and most stable carbon pool in the world (Lal 2004), with a carbon storage capacity 3.3 and 4.5 times greater than that of the atmospheric and biological carbon pools, respectively (Batjes 2016; Lal 2008; Lehmann et al. 2015). Consequently, minor alterations in the soil carbon reservoir can have a substantial impact on atmospheric CO2 levels. In particular, agriculture activities contribute to 17% of global carbon emissions (Delgado-Baquerizo et al. 2017), with CO2 from soil respiration being the largest source of atmospheric CO2 (Bradford et al. 2016; Falkowski et al. 2000; Lal 2008; Lehmann et al. 2015). Soil organic carbon (SOC) serves as the largest organic carbon pool on land (Bradford et al. 2016), whether soil acts as a carbon source or sink for atmospheric CO2 under global warming climate conditions depends on the rate of SOC decomposition (Davidson et al. 2006; Friedlingstein et al. 2020). Thus, it is essential to focus on the stability of organic carbon and soil respiration to help reduce the rise in atmospheric CO2 levels and anticipate climate change.

The terrestrial carbon and nitrogen (C-N) cycles are tightly coupled, with nitrogen inputs significantly impacting the soil carbon pool (Vitousek 1994). The potential for soil carbon sequestration is strongly correlated with N inputs (Bradford et al. 2016; Fang et al. 2017; Hurbert et al. 2020; Liang et al. 2017; Tipping et al. 2016). N input affects soil carbon sequestration potential mainly by altering soil microbial activities, which subsequently influences the microbial-mediated decomposition of SOC and dissolved organic carbon (DOC) (Xiao et al. 2019). N additions can increase soil N effectiveness (Buchkowski et al. 2017; Tripathi et al. 2018; Zhaltsina et al. 2015), which promoted soil C accumulation mainly by decreasing soil respiration (de Vries et al. 2014; Jansson et al. 2010; Liu et al. 2010; Zhang et al. 2018) and stimulating plant carbon exudation (Chen et al. 2019; Chen et al. 2021c; Pessoney et al. 2020; Wu et al., 2024). However, the opposite effect also exists: N addition promotes microbial respiration by increasing organic matter inputs and decreasing N limitation to microorganisms, which hinders soil C accumulation (Allison et al. 2009). There remains uncertainty regarding the decomposition of soil carbon pools (especially SOC and DOC) due to N inputs, and the impact of N inputs on the stability of soil carbon pools is not yet fully understood (Jiao et al. 2021; Feng et al. 2022; Lu et al. 2021). Therefore, studying the effect of N inputs on the soil carbon cycle process is essential for providing an theoretical foundation for the global carbon balance.

It has been found that the quality of exogenous substrate added into soils determines their effect on soil carbon mineralization. Han et al. (2022) found that green manure and straw fertilizers affected soil C mineralization by influencing key microbial taxa involved in soil C mineralization. Yang et al. (2023) suggested that different N applications affected soil C pools, primarily by modifying the abundance of carbon cycle genes and enzymes responsible for the degradation of soil organic carbon (SOC), particularly those related to the breakdown of cutinlike and resistant carbon. Previous studies have extensively explored the effects of various N input forms, such as chemical nitrogen fertilizers, biochar, and biochar combined with chemical nitrogen fertilizer on soil organic carbon cycling (Zhang et al. 2022; Zhang et al. 2023). Zhang et al. (2018b) proposed biochar-loaded NH+ 4-N as a novel form of nitrogen input, which can effectively reduce the emission of the greenhouse gas N2O by adsorbing NH+ 4-N through complexation, cation exchange, and electrostatic attraction. Biochar is a carbon-dense material created via pyrolysis in an environment with limited oxygen, exhibiting a high degree of stability (Leng et al. 2019; Li et al., 2024; Weber et al. 2018). Numerous studies have concluded that biochar offers a promising route to achieving net zero emissions (Cayuela et al. 2014; Lehmann et al. 2021; Nan et al. 2020; Sui et al. 2016). Biochar production and application can effect up to 12% of carbon emissions from human sources (Woolf et al. 2010). However, it is not yet clear how N input forms such as biochar loaded with NH+ 4-N affect organic carbon turnover. Extracellular enzymes secreted by microorganisms directly isolate soil carbon and nitrogen. The remaining portion (up to as large as 40%) can be released into the soil environment (Sinsabaugh et al. 2008). Enzymatic activities are closely linked to the activity of specific carbon degrading enzymes expressed by microbial communities.

Therefore, this study conducted a 180-day soil incubation experiment with the following objectives: (1) to investigate the impacts of biochar-enhanced NH+ 4-N on soil carbon emissions and the fractions of organic carbon, and (2) to shed light on the microbiological mechanisms underlying how biochar-loaded NH+ 4-N affects the stability of organic carbon; (2) biochar loaded with NH+ 4-N affects the activities of carbon-degrading enzymes and microorganisms; and (3) biochar affects microbial utilization of carbon by altering the structure of organic carbon, ultimately influencing soil carbon emissions.

## 2 Materials and methods

### 2.1 Soil and biochar preparation

The soil sample was collected from the 0–20 cm soil layer at the Qingdao Tobacco Resources and Environment Field Scientific Observation and Experimental Station of the Chinese Academy of Agricultural Sciences (36°20′ N, 120°14′ E). After homogenization and drying, the soil was sieved through a 2-mm mesh. The soil utilized in this experiment was classified as Alfisols according to the Alfisols (FAO Soil Taxonomic System), with the fundamental chemical properties prior to the test detailed in Table S1.

Biochar is prepared from biogas, and the preparation process of biogas can be found in previous reports (Zheng et al. 2020; Zheng et al. 2018c; Zheng et al. 2018b). The biochar preparation process is as follows: the pyrolysis temperature is 700°C, the heating rate is set at 5°C per minute, with a residence time of 60 minutes, and nitrogen (N2) is used as the inert shielding gas at a purity of 99.999% and a flow rate of 0.5 dm³ per minute. After biochar pyrolysis was complete, the biochar was pulverized, sieved through a 0.25-mm mesh, and stored in a dryer for later use, designated as BC. The preparation process for biochar-loaded NH+ 4-N is as follows: the loading solution is NH4Cl (1000 mg L−1), and the pH of the conditioning solution is 7.0. The biochar amount is 40 g L−1, shaken in a Constant Temperature Oscillation Chamber (25°C; 140 r min-1) for 48 h, centrifuged (4000 r min-1, 10 min), filtered and air-dried for 48 h. The NH+ 4-N loading of biochar is determined by calculating the concentration difference of NH+ 4-N in the solution before and after adsorption. The loading amount of biochar NH+ 4-N used in this experiment was 1.1975 mg g-1, and the biochar loaded with NH+ 4-N was labelled BC-N. The main physicochemical properties of DC and BC-N are summarized in Table S2.

### 2.2 Incubation experiment

Four different treatments were established for the incubation experiment: (1) blank control without fertilization (CK); (2) one-time application of synthetic nitrogen fertilizer (analysis of pure NH4Cl) (CF); (3) Biochar in conjunction with synthetic nitrogen fertilizer (BF); (4) biochar-loaded NH+ 4-N ( BN. The nitrogen content in each treatment was calculated to be consistent with the field nitrogen application rate (20.56 mg pure NH4Cl added for the BF treatment). The amount of biochar added in BF and BN treatment was 1.68 g.

The specific procedure of the test was as follows: 100 g of air-dried soil was placed into a 500 mL jar, and sterilized water was added to reach 30% of the maximum field moisture capacity. All soil incubations were initially cultured in a dark environment at 25°C for a period of 30 days, with the jar sealed using parafilm jelly and parafilm. After that, nitrogen fertilizer and/or biochar was thoroughly mixed with the soil, and the water was replenished to 60% of the maximum field moisture capacity. All soil samples were placed in jars containing 15 mL centrifuge tubes with 10 mL of 2 mol L-1 NaOH, as well as 10 mL centrifuge tubes with 5 mL of HCl. Three blank controls without soil samples were set up under the same conditions. At the beginning, incubation of 0–14 d, NaOH solution was replaced every 2 days, and then, NaOH solution was replaced every 7 days during 15–117 d. After that, NaOH solution was replaced every 14 days until day 181 d. Sterilized water was added during incubation to maintain a constant incubation weight. All soil samples were held at 25°C in a dark room for 181 days. After 7 days and again at 180 days of incubation, three samples from each treatment were randomly and destructively collected to measure CO2 emissions, carbon-degrading enzyme activity, and metagenomic sequencing. Soil collected from each jar was separated into three parts: one portion (40 g) was promptly utilized for the analysis of dissolved organic carbon (DOC) fractionation and microbial biomass carbon (MBC); another portion (20 g) was dried in the air for the fractionation and analysis of soil organic carbon (SOC) content, along with other chemical measurements including available phosphorus, available potassium, ammonium nitrogen, and nitrate nitrogen; the remaining portion (40 g) was kept at -80°C for the extraction of soil DNA and subsequent sequencing.

### 2.3 Measurements of soil respiration and biochemical properties

The soil cumulative carbon emission (soil respiration) was calculated (Xie et al. 2022) as described below: 5 mL of 1%NaOH was transferred to a 150 mL triangular flask, followed by the addition of 5 mL of 2 mol·L-1 BaCl2 and 1–2 drops of phenolphthalein . The solution was then titrated with 0.1 mol·L-1 HCl until the red color disappeared. The volume of HCl used was recorded, and the amount of soil CO2 emission was calculated. The calculation formula is given in Equation (1).

$$CO2\ emission\ (mg\ g\text{-}1) = (V0\text{-}V1) \times cHCl \times MCO2/m \quad \text{Equation (1)}$$

Where V0 represents the volume of HCl used to titrate the blank (mL), V denotes the volume of HCl utilized to titrate the sample (mL), cHCl indicates the concentration of hydrochloric acid (mol·L-1), M is 22 mg mmol-1, and SW refers to the dry weight of the soil (g).

The results of carbon mineralization in the soil were modelled using a first-order function, as well as first-order and zero-order functions, according to the following Equations (2) and (3).

$$Cm = C0 \times (1\text{-}\exp(\text{Equation (2)}$$

$$Cm = C0 \times (1\text{-}\text{Equation (3)}$$

Where Cm represents the mineralized C (g C kg−1 dry soil) after 180 days of incubation, and t denotes the incubation time (days). In the first-order function, C0 indicates potentially mineralizable C (g C kg−1 dry soil), and k is the rate constant (day−1). In the combined first- and zero-order function, CR refers to rapid potentially mineralizable C (g C kg−1 dry soil), and k is the rapid rate constant (day−1). Ac (g C kg−1 dry soil·day−1) signifies the rate of slowly mineralizable C equivalent to "CS ×kS," where CS represents slowly mineralizable C and kS is the slow rate constant).

Soil pH was assessed with a Sartorius PB-10 pH meter using a 1:2.5 ratio of soil to deionized water. Available phosphorus (AP) was measured by the molybdenum-antimony colorimetric method, while available potassium (AK) was quantified using the ammonium acetate leaching-flame photometric technique. Soil ammonia nitrogen (NH+ 4) and nitrate nitrogen (NO− 3) were extracted using 2 mol·L-1 KCl and determined using a flow injection autoanalyzer (SEAL-AA3, Germany). Soil organic carbon (SOC) was analyzed using an HT1100Exa Analyzer (Jena Analytik, Germany) analyzer. Total nitrogen (TN) was determined using the Semi-Micro-Kjeldahl method. Microbial biomass carbon (MBC) was determined utilizing chloroform extraction methods, while dissolved organic carbon (DOC) was extracted with 0.5 mol·L-1 K2SO4 and determined using IC5000+MultiC/N3100 (Jena Analytik, Germany) analyzer. β-glucosidase (S-β-GC), β-xylosidase (S-β-XYS), N-acetyl-β-glucosaminidase (S-NAG), and cellulase diisocharide hydrolase (S-CI) were determined using fluorescence analysis with 96-well enzyme-labelled plates.

### 2.4 SOC and DOC fractionation

The fractionation of soil organic carbon was analyzed employing solid-state 13C nuclear magnetic resonance (13C-NMR) combined with cross-polarization and magic-angle spinning (CPMAS). The procedure included weighing 7.5 g of soil into a centrifuge tube and then adding 50 mL of a 10% HF solution. The mixture was shaken at 25°C for 1 hour (300 r min−1), centrifuged at 3500 rpm for 10 minutes, and the supernatant was subsequently discarded. The procedure was repeated eight times, with the shaking durations of 1 hour (repeated four times), 12 hours (repeated three times), and 24 hours (once). Afterward, the sample was washed with deionized water and freeze-dried. A neutral pH, freeze-dried, and then ground sample (at 60 g) was packed into a 4-mm ZrO2 rotor at a 7 kHz rotation speed. The 13C resonance frequency was set at 100.625 MHz and chemical shifts were calibrated with the standard glycine. The measurement parameters consisted of a sampling time of 10 ms, a contact time of 10 ms, a spectral width of 100 kHz, a pulse width of 4 μs, a cycle delay of 1 s, and a total of 4096 scans. Functional group areas were calculated using MestReNova software. The spectra were integrated as follows: 0–45 ppm (Alkyl-C), 45–110 ppm (O-Alkyl-C), 110–165 ppm (Aromatic-C), 165–210 ppm (Carbonyl-C). Aliphaticity (Alkyl-C/O-Alkyl-C ratio), aromaticity (Aromatic-C/O-Alkyl-C ratio), and combined index (Alkyl-C × Aromatic-C/ O-Alkyl-C ratio) were calculated as indicators of soil organic carbon decomposition.

To analyze the structure of soil water-soluble soil organic carbon (DOC), dissolved organic matter was extracted with fourier-transform ion cyclotron resonance mass spectrometry (FTICR-MS) was employed. The DOC extracted from the soil involved the following steps: 2 kg of fresh soil was weighed, and 20 mL of ultrapure water was added. The mixture was shaken at a constant temperature of 25±1°C for 8 hours. Subsequently, the sample was centrifuged at 4200 rpm for 20 minutes, and the supernatant was filtered through a 0.22 μm filter membrane. The DOC concentration in the supernatant was measured after undergoing solid-phase extraction (SPE) purification using Agilent Bond Elut PPL. The SPE procedure included adjusting the sample pH to 2.0 with 1 mol·L -hydrochloric acid, followed by the addition of 12 mL of methanol and 12 mL of 0.01 mol·L -HCl to activate the SPE column. Next, the sample was gradually introduced into the column at a flow rate of about 2 mL min−1. After the sample had been processed, 18 mL of 0.01 mol·L -HCl was utilized to rinse the column and remove any salts. The column was then dried with a nitrogen stream, and the organic compounds were eluted using 12 mL of methanol. The collected eluate was evaporated to dryness under a nitrogen flow. Finally, the residue was reconstituted in 1 mL of a 1:1 aqueous-methanol solution prior to FT-ICR-MS analysis. The samples were analyzed using a SolariX FT-ICR-MS system from Bruker. Ionization was conducted in negative ion mode through electrospray ionization (ESI). Key instrument parameters included a continuous injection rate of 120 μL h−1, a capillary inlet voltage of −4.0 kV, an ion accumulation time of 0.06 seconds, and a mass range of 300 to 1000 Da. Data were recorded in a 64 32-bit format, incorporating 100 supercositions of time-domain signals to enhance the signal-to-noise ratio. The instrument was calibrated with 10 mmol·L -sodium formate before sample detection, and an internal standard was calibrated with soluble organic matter. After calibration, mass errors were maintained at less than 1 ppm.

The degree of unsaturation (DBE) and aromaticity (AI) of the DOC fractionation were calculated based on the molecular formula(ColthOrbeNpSq), using the formulas in Equations (4) and (5).

$$DBE = 1 + 2c - h - p + q/2 \quad \text{Equation (4)}$$

$$AI = (1 + c - 0.5o - s - 0.5h)/(c - 0.5o - s - n - p) \quad \text{Equation (5)}$$

Where c, h, o, n, and s are each represent the number of atoms of C, H, O, N, and S.

The Kow value of DOC was calculated by the weighted atom contributing according to Equation (6):

$$Mw = \sum (Mi * Ni) / \sum Ni \quad \text{Equation (6)}$$

Where Mi can represent O/C, H/C, DBE and AI, respectively, n represents the weighted average calculation, Ii and Mi are the relative content and the Mi value at i set, respectively, and the S relative content in the ratio of each peak intensity relative to the References peak.

### 2.5 Extraction of DNA, Construction of Libraries, and Metagenomic Sequencing

Genomic DNA was extracted from soil samples utilizing the Mag-Bind® Soil DNA Kit (Omega Bio-tek, Norcross, GA, U.S.) following the manufacturer's guidelines (Xu et al., 2021; Zhang et al., 2023). DNA concentrations were measured using a TBS-380 and a NanoDrop2000, respectively. The quality of the extracted DNA was assessed by electrophoresis on a 1% agarose gel. The DNA was then fragmented to an average size of approximately 400 bp using the Covaris M220 (Gene Company Limited, China) to prepare for paired-end library construction. The paired-end library was created using the NEXTFLEX Rapid DNA-Seq Kit (Bioo Scientific, Austin, TX, USA). Adapters with the complete set of sequencing primer hybridization sites were ligated to the blunt ends of the fragments. Paired-end sequencing was conducted using an Illumina NovaSeq (Illumina Inc., San Diego, CA, USA) at Majorbio Bio-Pharm Technology Co., Ltd. (Shanghai, China) using the NovaSeq 6000 S4 Reagent Kit v1.5 (300 cycles) according to the manufacturer's instructions (www.illumina.com). The data were annotated and analyzed using the non-redundant protein sequence set and the amino acid sequence databases of non-redundant proteins (NR) and carbohydrate-active enzymes (CAZy).

### 2.6 Statistical analysis

Genes responsible for expressing S-β-XYS, S-β-GC, S-NAG, and S-CI enzymes were identified based on the CAZy database. The following GH1–3, GH11, GH30 (GH30_1–GH30_9), GH39, GH43 (GH43_1– GH43_37), GH51, GH52, GH54, GH116 and GH120 enzymes S-β-XYS activity. GH3, GH5 (GH5_1, GH5_2, GH5_24– GH5_43, GH5_45–GH5_49 and GH5_51–GH5_56), GH9, GH30 (GH30_1–GH30_9) and GH116 enzymes S-β-GC activity. GH3, GH18, GH73, GH84, GH85, GH101, GH116 and GH163 enzymes S-NAG activity. GH5 (GH5_1, GH5_2, GH5_4–GH5_22, GH5_24–GH5_43, GH5_45–GH5_49 and GH5_51–GH5_56), GH8, GH9, GH30 (GH30_1–GH30_9) and GH116 enzymes S-β-GC activity. Microbiological-related analysis were performed using sequencing, and annotated by MajorBio Cloud (www.majorbio.com). A one-way analysis of variance (ANOVA) along with Welch-Duncan post hoc tests was employed to compare the soil and biochemical properties, soil carbon emissions, chemical composition of SOC and DOC, carbon degrading enzymes, the carbon degrading enzyme genes, microbial diversity, and community composition under different nitrogen inputs. Principal coordinate analysis (PCoA) based on Bray-Curtis dissimilarity was performed to explore the similarities in microbial community carrying the carbon-degrading enzyme genes S-β-XYS, S-β-GC, S-NAG, and S-CI. Permutational multivariate analysis of variance (PERMANOVA) was utilized to evaluate the impact of varying nitrogen inputs on microbial communities expressing these enzymes. The final equations were derived using SPSS 2021.

## 3 Results

### 3.1 Impacts of biochar-loaded NH+ 4-N on soil CO2 emissions

Different forms of N altered the cumulative soil carbon emissions (Fig. 1). As shown in Fig. 1a, daily CO2 emissions peaked around day 7 for all treatments, followed by a trough at day 30, after which the daily CO2 emissions gradually levelled off. On day 7, the daily CO2 emissions for the BF treatment were significantly greater than those observed in the other treatments. The cumulative CO2 emissions of the treatments after 180 days of incubation were ranked as follows: BF>CK>CF>BN. Compared to chemical fertilizer-only treatment, cumulative CO2 emissions in treatment of biochar mixed with chemical fertilizer BF increased by 50.16%, while those for biochar-loaded NH+ 4-N treatment decreased by 10.57%. These results suggest that biochar loaded with NH+ 4-N can effectively mitigate soil carbon emissions.

Soil C-mineralization was modelled with various forms of nitrogen input conformed to a combined first- and zero-order kinetic model (Fig. S1 and Table S3). The BF treatment increased C-mineralization (1.79±0.16g C kg-1 dry soil) in both the recalcitrant and labile C components compared to CF (2.53±0.04 g C kg-1 dry soil), whereas the BN treatment decreased C-mineralization (2.26±0.01 g C kg-1 dry soil) in both components. This indicates the C-mineralization in both recalcitrant and labile C pools varied with different forms of N input, where the recalcitrant C is more resistant to microbial decomposition than the labile C. Discrepancies rapidly by microbial metabolic activity during the initial stage.

### 3.2 Composition and structure of soil organic carbon

#### 3.2.1 SOC structure

Solid-state 13C-NMR showed shifts in the major carbon types among different N input treatments (Fig. S2). After 180 days of incubation, the organic carbon functional groups in the soil were primarily composed of O-alkyl-C, with alkyl-C and aromatic-C following in abundance, and the lowest proportion of carbonyl-C for all treatments (Fig. S2 and Table 1). Compared to chemical fertilizer (BF) and biochar-loaded NH+ 4-N (BN) significantly reduced alkyl-C, aliphaticity and the combined index by 16.27% and 22.16% (alkyl-C), 22.67% and 34.67% (aliphaticity), and 14.50% and 27.89% (combined index), respectively. Conversely, BN increased by 8.25% and 18.13% the relative both BF and BN treatments, respectively (Table 1). While the significant differences were found in the proportion of aromatic-C, carbonyl-C and aromaticity. In conclusion, both BF and BN increased labile organic carbon content while reducing recalcitrant organic carbon content. Additionally, biochar-loaded NH+ 4-N additives resulted in a great increase in labile organic carbon and a more significant decrease in aliphaticity and the combined index compared to biochar mixed with chemical fertilizer.

As shown in Fig. 2 and Table 2, the components of soil dissolved organic carbon (DOC) at day 180 were primarily composed of lignins, condensed aromatics, and tannins, which accounted for 39.58%-46.18%, 23.46%-30.28%, and 14.82%-18.77%, respectively. Compared to CF, BF and BN treatments increased condensed aromatics by 21.32% and 27.82%, respectively, while unsaturated hydrocarbons decreased by 21.82% and 44.26%, respectively. Additionally, the content of lignins, which are difficult to degrade, decreased by 11.05% and 13.16%, respectively (Fig. 2f and Table 2). The weighted mean (w) of DOC (Table 3) showed that the DBE-w values were similar between BF and BN treatments. While the Aln increased by 6.31% and 12.64% in BF and BN treatments, respectively, compared to CF treatment. The change may be attributed to the decrease in unsaturated hydrocarbons and the increase in condensed aromatics, which ultimately resulted in similar DBE-w values. Compared to BF, BN treatment increased the weighted mean value of soil condensed aromatics in DOC components, thereby enhancing the relative stability of DOC.

### 3.3 Impacts of biochar-loaded NH+ 4-N on soil carbon-degrading enzyme activity

With the extension of incubation time, the activity of S-β-XYS activity showed an increasing trend, while the activities of S-β-GC, S-NAG and S-CI decreased (Fig. S3). Specifically, compared to CF, S-β-XYS activities increased significantly by 12.88% under BF and BN treatments on day 7, respectively (Fig. S3a), while S-CI activity increased by 15.15% under BF treatment on day 7 (Fig. S3d). On day 180, S-β-GC activity was significantly higher by 15.21% and 16.19% for BF and BN treatments, respectively (Fig. S3b), and S-β-XYS activity increased by 11.66% under BN treatment compared to CF treatment (Fig. S3a). No significant differences were found in S-NAG activity between CF, BF and BN treatments after 180 days of incubation (Fig. 5c), though all treatments showed increased activity compared to CK. The total number of reads for genes expressing the four carbon degrading enzymes (S-β-XYS, S-β-GC, S-NAG and S-CI) across treatments were also detected (Fig. 3). On day 7 gene abundance for these enzymes were similar among treatments. However, by day 180, significant increase was found in the abundance of S-β-XYS gene in CF, BF and BN treatments compared to CK group, while significant decrease was found in the abundance of S-NAG gene in these treatments compared to CK group. however, no significant differences were found in the abundance of these four genes between CF, BF and BN treatment (Fig. 3). Overall, the abundance of expressed enzyme genes mirrored the enzyme activities (Fig. S3), suggesting that S-β-XYS and S-β-GC mediated carbon process play key roles in regulating soil organic carbon turnover under biochar-loaded ammonia nitrogen input.

### 3.4 The composition of microbial communities

Taxonomic annotation analysis showed the taxa composition at the phylum level involved S-β-XYS, S-β-GC, S-NAG and S-CI genes, respectively (Fig. S4a–d). On day 7, different forms of nitrogen input treatments had little effect on species composition, while by day 180, different forms of nitrogen input significantly impacted the microbial composition involved in S-β-XYS, S-β-GC, S-NAG and S-CI genes. The relative abundance of Actinobacteria encoding all four genes was significantly higher in CF treatment compared to the BF and BN treatments. In contrast, other microbial groups e.g. Acidobacteria, Proteobacteria, Gemmatimonadetes, Bacteroidetes, which also encode all these genes were more abundant in the BF and BN treatments than in CF. Taxonomic annotation of top ten microbes encoded S-β-XYS, S-β-GC, S-NAG and S-CI genes was also analyzed at the genus (Fig. S6–h). The microbial composition changed significantly during the incubation time, but the difference between each treatment was not obvious. The relative abundance of Sphingomonas encoding all these four genes on day 7 was lower than on day 180 in all treatments. And Caenorhabditis is unique taxa to encode S-CI genes (Fig. S4h).

The PCoA results indicated a significant difference in the microbial communities expressing S-β-XYS, S-β-GC, S-NAG and S-CI across various nitrogen input forms (Fig. 4). The community structures of microbes at the genus level harboring these genes varied significantly among the different nitrogen inputs (PERMANOVA test: p < 0.001; Fig. 4). Microbial communities from days 7 and 180 were distinctly separated based on nitrogen input form at day 180, but were not clearly separated at day 7 (Fig. 4).

### 3.5 The connection between microbial communities that participate in SOC degradation and soil properties, soil CO2 emissions, enzymes activity and soil organic carbon components

PERMANOVA analysis was conducted to evaluate the impact of soil properties, CO2 emissions, carbon-degrading enzyme activities, and the chemical composition of SOC and DOC on the S-β-XYS, S-β-GC, S-NAG and S-CI - expressing microbial communities (Table 4). Besides, the DOC, AP and MBC significantly (p < 0.01) influenced the S-β-GC, S-NAG and S-CI - expressing communities. Among the carbon-degrading enzymes, S-β-GC enzyme activity significantly (p < 0.01) correlated with the S-β-GC expressing microbial communities. Moreover, the composition of SOC, e.g. carbonyl-C and alkyl-C significantly (p < 0.01) influenced the S-β-XYS, S-β-GC and S-NAG encoding microbial communities. While most of the DOC chemical composition e.g. condensed aromatics, carbohydrates and lignin showed no obvious influence (p < 0.08) on all these carbon-degrading genes expressing microbial communities.

Structural equation modelling revealed how different forms of nitrogen inputs influenced the microbial community composition and soil carbon emission, and showing that 95.1% of soil carbon emissions could be explained by the selected variables (Fig. 5). The composition of DOC showed significant positive correlation with soil carbon emission, while the SOC composition negatively correlated with carbon emission. Additionally, different N input forms played critical role in the microbial community composition, soil nutrients, as well as the cumulative carbon emissions (Fig. 5).

## 4 Discussion

### 4.1 Biochar-loaded ammonia nitrogen decreases soil carbon emissions by soil organic carbon reserves

Soil carbon emissions are strongly influenced by exogenous C and N additions. In our study, biochar-loaded NH4+ −N significantly reduced soil carbon emissions (Fig. 1) and decreased C mineralization in both recalcitrant and labile C pools (Table S3). In contrast, biochar combined application of chemical nitrogen fertilizer promoted soil carbon emissions (Fig. 1) and increased C mineralization in the stabilized and degradable C pools (Table S3). Prior research indicates that applying biochar can result in nitrogen limitation for soil microbial communities during the decomposition of biochar (Schimel et al. 2022). This promotes microorganisms' use of nitrogen from organic matter, leading to a positive priming effect that elevates soil carbon emissions (Wu et al. 2021). Conversely, other research has shown that biochar lowers soil carbon emissions by reducing the degradability of organic carbon (Chen et al. 2022). The addition of biochar provided soil microorganisms with survival sites and nutrients, which significantly increases both biomass and activity of soil microorganisms (Su et al. 2017; Xiao et al. 2015; Zhang et al. (2018b) found that biochar adsorbed ammonium nitrogen mainly through complexation, cation exchange, and electrostatic interactions. In contrast to the application of biochar alongside chemical nitrogen fertilizers, biochar-loaded ammonia nitrogen attracted ammonium nitrogen into the abundant pores of biochar (both internal and externally) through physical forces. This adsorption reduced ammonium nitrogen volatilization (Zhang et al. 2020; Zheng et al. 2018c; Zheng et al. 2018b) and allowed microorganisms that colonize the pores to access N directly, thus alleviating the microbial N limitation caused by biochar input. This, in turn, enables microbes to preferentially utilize the labile C fraction of biochar over the recalcitrant C fraction (Chen et al. 2021a).

Most of the carbon structures in biochar prepared by high-temperature pyrolysis is in a stable form, with aromatic carbon being the major component (Cheng et al. 2006; Liao et al. 2022; Maljanen et al. 2010; Orsetualdi et al. 2018; Yang et al. 2022a). Analysis using 13C-NMR and FTIR revealed that both the combination of biochar with chemical nitrogen fertilizer and the application of biochar-loaded ammonia nitrogen improved the aromatic structure of the added biochar in our study (Figs. S2 and 2, Tables S1, S2, and 1). Among them, the aromatic carbon content of DOC was higher in biochar-loaded with ammonia nitrogen compared to biochar + chemical nitrogen fertilizer (Fig. 2, Tables S3 and 2). Nevertheless, dissolved organic carbon (DOC) is unstable and highly degradable, significantly impacting soil carbon emissions (Yibe-Costa et al. 2020). Yang et al. (2022a) and He found a positive correlation between soil carbon emissions and DOC content, which aligns with our findings (Fig. 5). In this study, the application of biochar enhanced the levels of soil organic carbon pools (SOC and DOC) (Table 1-3), yet soil carbon emissions decreased with the biochar-loaded ammonia nitrogen treatment (Fig. 1). Chen et al.(2021) showed that adding biochar enhanced the aromatic structure of soil SOC and DOC, thereby improving the stability of the soil carbon pool. Due to the higher content of aromatic structures in biochar, the soil carbon pool was more stable, and the carbon emissions were lower.

### 4.2 Biochar-loaded ammonia nitrogen affects carbon degradation enzymes and microbial composition, indirectly influencing soil carbon emissions

Differences in soil nutrient composition and nitrogen input form alter the activity of carbon-degrading enzymes and microbial composition, thereby affecting the composition of organic carbon and consequently influence the soil carbon emission (Figs. 1 and 5; Table S4). S-β-GC and S-β-XYS were used as enzymes for degrading unstable and stable carbon, respectively. Our study showed that biochar-loaded ammonia nitrogen input increased microbial secretion of extracellular enzymes S-β-GC and S-β-XYS, as evidenced by the detection of high enzyme activities and gene abundance (Figs. 3 and S3). However, the relative contribution of combined application of chemical nitrogen fertilizer and biochar to enzyme activity and gene abundance of S-β-GC (Fig. S3b; Fig. 3) The high adsorptive capacity, porous nature and carbon-rich properties of biochar contribute to significant biological, chemical, and physical impacts on the soil, stimulating or inhibiting microorganisms (Quilliam et al. 2013; Wang et al. 2017). When biochar adsorbs nitrogen fertilizer applied to the soil, it increases a chemophex (a soil microenvironment) (Yu et al. 2021), that provides microorganisms with sufficient C and N nutrients, promoting the secretion of extracellular enzymes like S-β-GC to degrade unstable carbon. In the early period (7 days), S-β-XYS enzyme activity increased rapidly in both biochar-applied treatment compared to fertilizer alone. In the later period (180 days), S-β-XYS enzyme activity was significantly higher in the biochar-loaded ammonia nitrogen treatment compared to the other treatments (Fig. S3a). In contrast to the joint application of biochar and chemical nitrogen fertilizer, the nitrogen in biochar-loaded ammonia nitrogen exhibited greater stability (Zheng et al. 2018a; Zheng et al. 2018b). The adsorbed reduced ammonium nitrogen loss through ammonia volatilization (Zheng et al. 2018c) and provides microorganisms with a continuous source through the slow release of ammonia nitrogen. This stability allows microorganisms to maintain steady metabolic activities while minimizing the stimulation of microbial activities caused by fertilizer inputs. Furthermore, this process alleviates the soil N limitation induced by biochar input and suppresses the positive initiation effect typically triggered by such inputs. This finding suggests that biochar-loaded ammonia nitrogen facilitates long-lasting and sustained decomposition of stabilized carbon, enhances soil carbon pool stability, and reduces soil carbon emissions.

Soil microbial communities are crucial in regulating soil carbon emissions and organic carbon performance (Wang et al. 2021). This study revealed subtle differences in the microbial community compositions of microorganisms that express the four carbon-degrading enzymes. At the phylum level for the top six microbial groups by relative abundances were identical (Fig. S4a, b, c, and d), while At the genus level, however, the relative abundances of microorganisms that express the four carbon-degrading enzymes differed significantly (Fig. S6a, c, g, and h). Biochar application reduced the relative abundance of Sphingomonas in the biochar-loaded ammonia nitrogen treatment (Fig. S6a, c, g, h) was likely attributed to the degradation of polycyclic aromatic hydrocarbons by Sphingomonas, which consequently enhanced the impact of biochar on aromatic carbon in the soil (Chen et al. 2016; Dai et al. 2015). Alterations in microbial community structure allow microorganisms to preferentially utilize specific carbon fractions, affecting the structure and functions of SOC and DOC (Sun et al. 2020). PERMANOVA analysis revealed that the dominant factor influencing the structure of microbial communities expressing the four degradative enzymes were generally similar, with soil pH, MBC−N and NO3−N being the most influential factor on microbial community structure (Table 4). Both biochar and chemical nitrogen fertilizer application significantly affected soil pH (Zhaxi et al. 2021), along with ammonia volatilization, nitrogen fixation, and nitrogen loading (Nguyen et al. 2017), which altered the soil C/N ratio and consequently the microbial community structure changes (Wang et al. 2018).

## 5 Conclusion

The structural equation analysis revealed that different forms of N inputs significantly affected soil carbon emissions. Nitrogen input affected carbon degrading enzymes by altering soil properties and microbial community composition, which in turn influenced the composition of SOC and DOC, ultimately leading to changes in soil carbon emissions. Ammonia nitrogen-loaded biochar substantially decreased soil carbon emissions, boosted carbon-degrading enzyme activity, improved the stability of the soil carbon pool, and enhanced microbial composition. Future studies should aim to investigate the long-term impacts of biochar loaded with ammonia nitrogen.

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# Contrasting microbial C dynamics under different long-term P fertilization regimes in non-allophanic Andosols.

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## ABSTRACT

Soil carbon (C) plays a central role in the global C cycle with the potential to mitigate the elevated atmospheric carbon dioxide ($CO_2$) concentration by sequestering C into soil organic matter (SOM). Phosphorus (P) fertilization influences SOM decomposition and microbial processes, including microbial C use efficiency (CUE), determined as the ratio of C allocated to biomass growth to C respired as $CO_2$. Non-allophanic Andosols are characterized by high organic C contents and strong P retention, but the effects of long-term P fertilization on C dynamics in these soils remain poorly understood. We conducted a 20-day incubation experiment to examine how soil P availability, driven by long-term fertilization practices, influenced microbial C dynamics in non-allophanic Andosols. We collected the soil samples from two contrasting P fertilization field (Truog-P: 157 mg $kg^{-1}$ or 12 mg $kg^{-1}$) in Tohoku University, Japan. Soil samples (100 g dry soil) were treated with water (control), $^{13}$C-glucose (450 mg C $kg^{-1}$), or glucose with ammonium sulfate (61 mg N $kg^{-1}$), and incubated at 25°C with 55% moisture content (w/w). Microbial CUE at the initial and latter stage of the incubation and SOM priming effects (PEs) during the incubation were measured.

Long-term P fertilization significantly influenced microbial respiration and CUE. In the high-P soils, glucose with N substrate addition resulted in negative PEs. In contrast, the low-P soils exhibited positive PEs under glucose addition, along with higher phosphatase activity and MBC:P ratios, suggesting that P limitation promoted microbial P-mining through SOM degradation. Furthermore, higher glucose-derived CUE was found in the high-P soils than in low-P soils at latter stage of the incubation. The low-P soils also maintained lower pH and higher exchangeable Al, conditions that, along with P limitation, likely constrained microbial respiration and CUE by increasing metabolic maintenance costs. Consequently, contrasting microbial C utilization between the soils were found, reflecting the combined effects of P deficiency and Al toxicity. This study demonstrated that CUE and substrate-induced SOM decomposition in non-allophanic Andosols is strongly influenced by the combined effects of long-term P fertilization.

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# Soil Carbon Storage Enhances Nitrogen Fixation by Accumulating Necromass-Bound Micronutrients

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**ABSTRACT**

Long-term fertilization is known to increase soil organic carbon (SOC) storage; however, the mechanisms linking SOC dynamics to biological nitrogen fixation (BNF) remain poorly understood. Here, using two long-term (>20 years) field experiments, we show that organic amendments significantly enhanced SOC storage by increasing reactive minerals in both corn-wheat rotation and paddy soils. Coincident with this C accumulation, long-term manure fertilization enriched microbial necromass and short-range ordered iron (oxyhydr)oxides. This enrichment elevated Molybdenum (Mo) storage and bioavailability, which in turn increased *nifH* gene abundance and nitrogenase activity. Metagenomic sequencing further revealed that micronutrient bioavailability was strongly correlated with the abundance of key N-fixing genera (e.g., *Azospirillum* and *Bradyrhizobium*). Crucially, structural equation modeling identified microbial necromass as the primary driver of N-fixing populations, highlighting an underappreciated role of necromass as a micronutrient reservoir. We conclude that micronutrient bioavailability is a critical factor regulating BNF in paddy soils, offering significant implications for sustainable nutrient management.

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# Long-Term Variability of Peat Soil Properties and $CO_2$ Flux in a Planted Forest Ecosystem

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**ABSTRACT**

Tropical peatlands are major global carbon stores, yet their soil properties and $CO_2$ flux dynamics can shift over time through natural processes and land management. Detecting such long-term changes is essential for improving carbon assessments and ensuring that measurement approaches capture the unique behavior of peat soils. This study examines 25- year changes in peat soil properties and $CO_2$ flux in a planted tropical peat forest in Bukit Batu, Riau Province, Indonesia. Soil sampling at 0–30 cm depth evaluated physical, chemical, and biological indicators, encompassing moisture content, bulk density, ash content, and microbial biomass. Using a closed-chamber method, $CO_2$ fluxes were measured in blocks with excised and intact roots to obtain more accurate soil-derived fluxes. Measurements on the same undisturbed samples were also conducted in Bogor for comparison.

Over 25 years, surface peat conditions changed noticeably, with moisture declining, bulk density and ash content increasing, and microbial biomass decreasing. In contrast, the peat remained hemic but exhibited a finer material structure. Correspondingly, soil $CO_2$ flux in 2025 dropped by approximately 46–67% compared to 2010, reflecting not only reduced soil moisture and microbial activity but also decreased root-derived respiration. Microclimatic differences, including the absence of weeds in 2025, contributed to these changes. These findings highlight the importance of long-term, multi-parameter monitoring and show that peat-adapted flux measurement methods can enhance the accuracy of emissions estimates in peatland.

**Keywords:** $CO_2$ flux; peat decomposition; root exclusion; soil properties; tropical peatland

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# Regulating soil organic–inorganic carbon trade-offs through integrated nitrogen and organic fertilization

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## ABSTRACT

Long-term intensive management, particularly continuous nitrogen fertilization, induces soil acidification, accelerating carbonate dissolution and leaching and thereby generating a trade-off between soil organic and inorganic carbon (SOC, SIC) that constrains agricultural sustainability. Based on a 20-year field experiment, this study quantifies the vertical distribution, transformation pathways, and net carbon balance of soil carbon components under contrasting nitrogen and organic inputs. Results showed that long-term N fertilization caused pronounced surface acidification (~0.4 pH-unit decline), inducing a strong SOC–SIC trade-off in the 0–20 cm layer that maintained surface total C stocks across most treatments. Profile-scale analysis revealed that surface-based assessments masked substantial carbon losses: N-only fertilization accelerated carbonate dissolution and downward leaching of dissolved inorganic carbon, resulting in a marked net carbon deficit across the profile (_1.2 Mg C ha_1 yr_1). Isotopic evidence showed that organic inputs promoted the conversion of biogenic carbon into pedogenic carbonates (PIC), with PIC increasing with organic input intensity, but sequestration efficiency differed among amendments. Straw return increased cation exchange capacity but failed to prevent base-cation depletion and SIC loss. In contrast, manure combined with N substantially enhanced SOC and nutrient status and, through shifts in δ13C signatures and PIC/LIC depth patterns, revealed a coupled pathway of organic C mineralization, carbonate dissolution–reprecipitation, and PIC formation. Notably, high-rate manure plus N (2CM+Nl) both supplied exogenous carbon and buffered acidification, achieving coordinated accumulation of SOC (+l.3 Mg C ha_1 yr_1) and PIC (+0.l3 Mg C ha_1 yr_1) across the profile and a net sequestration rate of 2.1 Mg C ha_1 yr_1. Overall, N-driven acidification vertically decouples SOC and SIC dynamics, indicating that carbon accounting in calcareous croplands must explicitly include SIC and optimize organic inputs and N management to sustain long-term multi-pool carbon sequestration.

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# Effects of Eucalyptus robusta afforestation on soil carbon fractions and the underlying mechanisms

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**ABSTRACT**

Afforestation patterns are a critical factor influencing the stability and sequestration potential of soil carbon pools. However, the impact of Eucalyptus robusta afforestation on soil carbon stability and its key regulatory mechanisms remains unclear. This study focused on five plantation types with similar stand ages: Eucalyptus robusta monoculture, Pinus massoniana monoculture, Cunninghamia lanceolata monoculture, Eucalyptus robusta-Pinus massoniana mixed plantation, and Eucalyptus robusta-Cunninghamia lanceolata mixed plantation. Soil samples were collected from the 0-20 cm layer for systematic analysis of pH, moisture content, clay, silt, and sand content; total carbon (TC), total nitrogen (TN), total phosphorus (TP), ammonium nitrogen, and nitrate nitrogen; soil organic carbon (SOC), particulate organic carbon (POC), mineral-associated organic carbon (MAOC), and iron-bound organic carbon (FeOC); iron and aluminum oxides (in free, amorphous, and complexed forms); as well as amino sugars, lignin phenols, and phospholipid fatty acids (PLFA). The aim was to elucidate the effects of afforestation patterns on soil carbon stability and their underlying driving mechanisms.The results indicated that afforestation patterns significantly altered the distribution of soil carbon fractions, the iron/aluminum oxide-bound carbon pool, and the structure and activity of microbial communities. Compared to monocultures, mixed plantations (particularly the Eucalyptus robusta- Cunninghamia lanceolata mix) exhibited a higher proportion of MAOC and stronger protective effects of iron/aluminum oxides on organic carbon. Concurrent changes were observed in microbial community composition and indicators related to carbon transformation functions, suggesting an enhancement of carbon-mineral-microbial interactions. These differences collectively contributed to enhanced long-term soil carbon stability.This study demonstrates that rational mixed-species afforestation can improve soil carbon sequestration capacity by optimizing carbon fraction allocation, enhancing mineral protection, and regulating microbial processes, thereby providing a scientific basis for the sustainable management and carbon stewardship of plantation forests.

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# Impact of burning cessation on soil carbon stocks and organic matter fractions in semi-natural grasslands

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## ABSTRACT

Grasslands cover 40% of terrestrial land area and semi-natural grassland in Japan store large amounts of soil carbon. In Japan's Aso region, annual burning maintains semi-natural grasslands dominated by *Miscanthus sinensis* (C4 plant), whereas burning cessation leads to succession toward C3 broadleaf forests. Previous studies have shown that discontinuing burning and allowing vegetation succession leads to a reduction in soil carbon. This study examined how burning continuation and cessation affect soil organic carbon (SOC) and SOM fractions during succession.

The study was conducted in the Aso region, Kumamoto Prefecture. The grassland maintained by burning for over 20 years (Burning : BR) and the adjacent site where burning ceased 10 years ago (Unmanagement : UM) were selected. BR was dominated by *M. sinensis* with some C3 plants, while UM was dominated by mainly C3 vegetation. Soils (0-30 cm with 5 cm increments, 3 replicates) were fractioned using sodium polytungstate (1.8 g $cm^{-3}$) and ultrasonification (800 J $ml^{-1}$) into free particulate organic matter (fPOM), occluded particulate organic matter (oPOM), and mineral-associated organic matter (MAOM). Total carbon and nitrogen content, and $\delta^{13}C$ were measured for bulk soils and each SOM fraction. Carbon contents were expressed as SOC (bulk soil) and fPOC, oPOC, MAOC (SOM fractions). Depth-specific differences in $\delta^{13}C$ ($\Delta\delta^{13}C$) and C/N ($\Delta C/N$) between BR and UM were calculated as indicators of SOM turnover. Additionally, aluminum ($Al_p$) and iron ($Fe_p$) derived from humic complexes were measured.

SOC stock at 20-25 cm and fPOC stock at 10-15 cm exhibited significantly higher in BR than UM. However, no significant differences were observed at other depths or SOM fractions. Depth-specific comparisons revealed that the 0-5 cm layer exhibited both management relatively abundant fPOC and oPOC, while MAOC was scarce. In the range of 5-30 cm, both fPOC and oPOC declined, and MAOC comprised the predominant proportion (62-78%). This trend in both management suggests strong influence of surface litter and char in the top soil layer. $\delta^{13}C$ and C/N of bulk soils and SOM fractions were lower in UM, reflecting rich in C3-derived carbon inputs. Notably, $\Delta\delta^{13}C$ of all SOM fractions and $\Delta C/N$ of fPOM peaked at 5-10 cm depth, indicating carbon turnover was most active at 5-10 cm depth rather than the surface (Fig 1). This may be due to (1) dense *M. sinensis* rhizomes below 5 cm and higher surface C3 inputs at BR, and (2) decline of *M. sinensis* rhizomes and deeper C3 root inputs after burning cessation. In BR, mean $\delta^{13}C$ and C/N of fPOM at 5-30 cm depth were -17.0‰ and 22.2, while these were -20.5‰ and 18.5 at 0-5 cm. This indicated that C3-derived carbon in BR contributed in the surface. Positive correlations between $Al_p$ or $Fe_p$ and MAOM, with UM exhibiting higher values than BR, suggests that the cessation of burning may increase the acidic functional groups in MAOM.

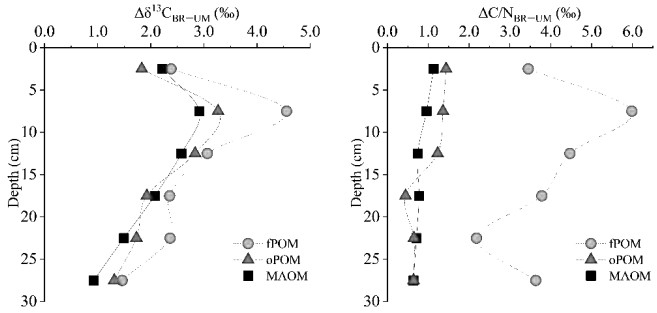



Fig. 1 Differences in $\delta^{13}C$ and C/N between continued burning and unmanagement at each depth (a) $\Delta\delta^{13}C$ (Burning - Unmanagement), (b) $\Delta C/N$ (Burning - Unmanagement)

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# Soil microbiomes exhibit threshold responses to oxygen isotope enrichment

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**ABSTRACT**

Water is fundamental to microbial metabolism, and $H_2{}^{18}O$ is widely used in stable isotope probing (SIP) to quantify microbial growth and activity. However, it remains unknown whether different levels of $^{18}O$ enrichment perturb microbial communities and functions, and what enrichment levels are suitable for ecologically realistic experiments. We tested soil microbiome responses across an $H_2{}^{18}O$ gradient (0.2-80 atom%), integrating full-length 16S rRNA gene sequencing, functional gene profiling, and physiological assays. We found that overall diversity remained stable, but community composition shifted, with ~6% of indicator taxa exhibiting clear threshold responses, including both increasing and decreasing taxa. Functional genes showed pathway-specific thresholds, with change points for genes involved in carbon fixation as well as nitrogen, phosphorus, sulfur, and methane metabolism clustering at intermediate enrichment levels (~ 33-39 atom%$^{18}O$). Microbial physiological traits showed contrasting sensitivities to $^{18}O$ enrichment: respiration declined sharply with a change point at relatively low enrichment (~22 atom%$^{18}O$), whereas microbial growth, carbon use efficiency, and turnover varied continuously along the gradient and did not exhibit identifiable thresholds. Our results demonstrate that $H_2{}^{18}O$ enrichment is not biologically inert, but instead elicits hierarchical and nonlinear responses across microbial organizational levels. Integrating responses across community, functional, and physiological dimensions, enrichment levels of approximately 20-30 atom%$^{18}O$ can be considered a conservative threshold range at which isotopic stress begins to emerge. Accordingly, to minimize isotope-induced physiological artifacts and improve comparability across studies, future SIP experiments should avoid exceeding this enrichment range.

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# Spatial variations of organic matter concent in cultivated land topsoil in North China based on updated soil databases

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## ABSTRACT

Accurate knowledge of spatial variations in organic matter content of cultivated land topsoil (CTSOM) is crucial for the effective use and management of cultivated land. However, this knowledge remains largely uncertain owing to outdated and imprecise soil databases. Therefore, in 2020, this study meticulously collected 918 samples of cultivated land topsoil (0–30 cm) in Hebei Province of North China, and a Random Forest (RF) model was used to delineate the spatial variability of CTSOM. Results indicated the robust performance of the RF model containing 21 predictors, with an $R^2$ of 0.77, and soil properties emerging as the most important predictors. The current mean CTSOM level in the study area stood at 16.47 ± 3.94 g $kg^{-1}$, displaying a spatial pattern with higher CTSOM levels in the western and northern mountainous areas, and lower levels in the eastern plain areas. A comparison with the second national soil survey data revealed that the overall regional level of CTSOM has increased by 4.28 g $kg^{-1}$ over the last 40 years. However, a significant decline in CTSOM was observed in the northern part of the study area, where straw return and fertilization can be key contributing factors. This study provides updated knowledge on the spatial variations of CTSOM in North China, which is valuable for agricultural ecosystem management worldwide and for carbon accounting in terrestrial ecosystems.

**Acknowledgments**

This study was funded by the National Natural Science Foundation of China (Project nos. 42171289 and 42201285), National Science and Technology Basic Resources Survey Special Project (Project no. 2021FY100403), and China Postdoctoral Science Foundation (2023M733781).

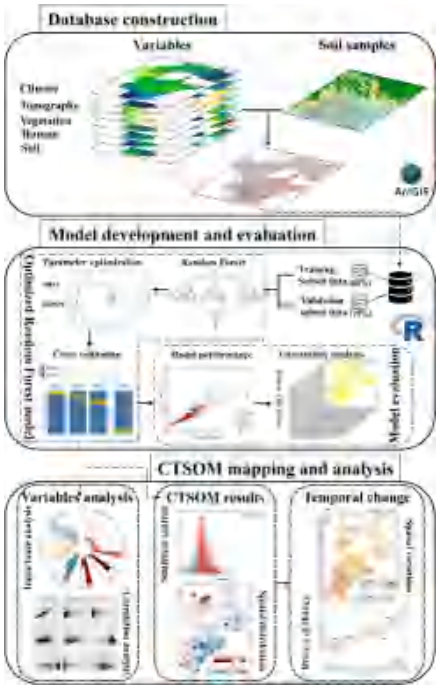



Fig. 1 Flowchart showing processing framework for mapping and analyzing CTSOM in the study area.

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# Digging Deeper: Increasing Precision in quantifying Soil Organic Carbon Losses After Forest-to-Cultivated Land Conversion

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## ABSTRACT

Accurate quantification of soil organic carbon (SOC) stocks is essential for evaluating land-use impacts, informing soil health assessments, and supporting carbon accounting frameworks. Comparisons between forest soils and adjacent cultivated lands provide valuable insight into the magnitude and depth distribution of SOC losses associated with agricultural conversion.

In this study, soil samples were collected to a depth of 1 m from a cultivated field and an adjacent forest at the Elora Research Station (Guelph, Ontario) to quantify SOC stocks and assess the relative contributions of topsoil and subsoil carbon. Soil organic carbon was determined using a muffle furnace method, and SOC stocks were calculated using an equivalent soil mass approach to account for differences in bulk density between land uses. The effects of land use and soil depth on SOC were evaluated statistically.

Soil organic carbon stocks were 180.6 Mg C $ha^{-1}$ in the cultivated site and 219.6 Mg C $ha^{-1}$ in the forest when expressed at an equivalent soil mass of 13,000 Mg $ha^{-1}$, representing an approximately 18% reduction following conversion from forest to agriculture. The majority of SOC loss (93%) occurred within the upper 30 cm, while subsoil layers accounted for a substantial proportion of total SOC stocks (52% in cultivated soils and 44% in forest soils). These results indicate that surface SOC is highly sensitive to land-use change, whereas subsoil SOC constitutes a significant and comparatively stable component of total SOC stocks.

Overall, this study highlights the importance of depth-resolved SOC assessment and standardized stock calculation methods for improving the precision of land-use comparisons and strengthening soil carbon accounting.

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# Long-term impact of integrated crop-livestock-forest systems on soil organic carbon sequestration and edaphic health in the Brazil

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## ABSTRACT

Land-use transitions shift soil biogeochemical flux; however, adopting conservation agriculture, notably integrated systems, optimizes productivity, sequesters carbon, bolsters biodiversity, enhances nutrient cycling, water infiltration and storage, and gaseous exchange. Consequently, integrated crop-livestock-forest systems (ICLFs) are a flagship of Brazil's "Low-Carbon Agriculture" program for greenhouse gas offset or mitigation through increased harvest efficiency. ICLFs support sustainable intensification by synergizing annual crop, forestry, and livestock activities within synchronized spatio-temporal frameworks in the same area and season. This system leverages crop rotation and no-tillage to optimize the volume and biochemical quality of surface residues, fundamentally enhancing soil organic carbon sequestration, edaphic quality, and functional health. ICLFs use crop rotation and no-tillage to optimize the volume and quality of above- and below-ground residues, enhancing soil organic carbon sequestration, edaphic quality, and functional health. A long-term ICLFS in São Carlos, SP, Brazil (21°57'S, 47°50'W, 860m), evaluated soil carbon sequestration and edaphic health across integrated management systems within the Atlantic Forest biome. Physical, chemical, and biological properties were quantified to a depth of 1.0 m across a 30-ha typic Haplorthox under Cwa climatic conditions. The experimental design comprised: i) intensive (INT) grazing in Palisade grass (*Urochloa brizantha*) pasture; ii) crop-livestock (ICLS) featuring interannual rotation of maize intercropped with Palisade grass; iii) crop-livestock-forest (ICLFS) integrating *Eucalyptus urograndis* (83 trees $ha^{-1}$) with ICLS; iv) livestock-forest (ILFS) combining Palisade grass and Eucalyptus; v) extensive (EXT) grazing of *Urochloa decumbens* pasture; and vi) a native Atlantic Forest fragment as a control. Results indicate that land-use transitions toward ICLFs, driven by adequate farm and soil management strategies such as balanced nutrient management, optimized grazing, no-till farming, and crop rotation and diversification, fundamentally bolstered the edaphic health. These systems optimized nutrient cycling and soil fertility. ICLFs also enhanced carbon sequestration throughout the soil profile and modulated organic matter stability compared with traditional pastures. Integrated systems exhibited substantial soil carbon accretion rates, exceeding 1.5 t C $ha^{-1}$ $year^{-1}$. Physical indicators, specifically saturated hydraulic conductivity, showed greater improvement in ICLFs than in extensive pastures, supported by the development of biogenic macroporosity. Furthermore, increased biological diversification stimulated macrofauna abundance, with earthworm populations emerging as highly sensitive bioindicators for tracking these management-induced transitions.

**Acknowledgments**

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# Vulnerable Zone of Soil Inorganic Carbon Loss in Intensive Agricultural Regions

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**ABSTRACT**

Soil carbon (C) comprises organic carbon (SOC) and inorganic carbon (SIC). The role of SOC in soil heath and climate change is well known and has received widespread attention. Although globally, SIC stocks in the upper 1 m soil profile are equal to nearly half of SOC in the same layer, our understanding of SIC dynamics and its contribution towards soil heath and climate change is still rudimentary, due to it is usually considered that SIC is very stable, and has a limited role in the global C cycle. In recent years, more evidences have indicated that the turnover rate of SIC is much faster than was thought. As a result, increasing researches have studied the SIC changes. More studies focus on SIC roles in sequestrating carbon and buffering soil pH, and relationship between SIC and risk of heavy metals pollution. The mechanism controlling SIC changes in intensive agricultural region, and the hotspot regions of SIC loss remain unclear.

We have built the database both by collecting the data from literatures and determining soil samples taken from the different provinces to study the driving forces of SIC content change in the top soil layer of farmland in China from the 1980s to the 2010s. It found that the changes of SIC density (SICD) in the 0-40 cm soil layer of farmland in China from the 1980s to the 2010s were significantly correlated with the ratio of rainfall (P)/potential evapotranspiration (PET) (drought index). The decaling rate of SICD in humid and semi-arid regions was increased with the P/PET ratio, and their relative changes were enhanced by high N fertilizer input. In contrast, the SICD was increased in arid regions. It conforms that the drought index and N fertilization are major drivers that lead to dramatic losses of SICD in croplands. In regions where carbonate content is low, and N application rate and P/PET are high, the SIC pool is vulnerable to lose. For example, soils in the transition zones between the North and the South China (Qinling Huaihe River), brown soil and alluvial soil in the Shandong Peninsula, black soil and chernozem in Northeast China. These regions are designated as vulnerable zone SIC loss. If SIC pool is consumed up, soil pH will drop dramatically. Several case studies in China will be introduced. For a sustainable reduction of SIC loss induced by soil acidification, the different measures are suggested, including adequate application of N fertilizers, combining the application of N fertilizers with organic fertilizer and nitrification inhibitors and replacing the ammonium bearing fertilizers with nitrate fertilizer.

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# Using Natural δ¹³C Signature from Both Soil Profiles and Topsoils to Understand Organic Carbon Transformation in Mollisols (Phaeozems) of Northeast China

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## ABSTRACT

Mollisols (black soils) are the most fertile and productive soils in the world, and their fertility are often associated with their high organic matter content. Their long-term cultivation has caused severe degradation including decline in soil organic carbon (SOC) content; however, the fundamental processes governing changes in carbon inputs, fractions transformation and turnover dynamics due to cultivation are still poorly understood. Here, we used stable carbon isotope ($\delta^{13}C$) and C/N ratios of bulk SOC and mineral-associated organic carbon (MAOC) analysis of five Phaeozems soil profiles and 30 pairs of cropland and natural topsoil samples along a latitude transect from Northeast China to document the organic matter source during soil formation, to understand the dynamics and transformation of SOC induced by cultivation, and to provide insights into soil conservation practices. Two profiles from the southwest steppe region show an upward increase of ca. 5‰ in $\delta^{13}C_{soc}$ from -26.3‰ to -21.4‰, suggesting progressive increases in C contributions from C4 plants expansion caused by increasing aridity and weakened summer monsoon during the late Holocene. In contrast, three profiles from the northeast forest region show a decrease of ca. 2‰ from -23.6‰ to -25.5‰ in $\delta^{13}C_{soc}$ and an increase in C/N ratios from 6 to 12 upward, a pattern consistent with greater microbial C inputs at depths. The enrichment of 1.8‰ in $\delta^{13}C_{soc}$ values on average in the plough horizon of all five profiles indicated impact of corn (C4 plant) cultivation. Also, similar enrichment was observed in 30-paired topsoil samples (0-30 cm), showing that the $\delta^{13}C$ values in cropland soils were higher (from -18.8‰ to -25.5‰, with a mean of -22.9‰) than natural soils (from -21.9‰ to -27.7‰, mean value is -25.2‰). The 2.3±0.5‰ enrichment of $\delta^{13}C$ in cropland topsoil indicated that corn cultivation contributed 12.3±6% to SOC. Furthermore, the $\delta^{13}C_{MAOC}$ were lower than $\delta^{13}C_{SOC}$ by 0.63‰ at 0-5 cm and 0.02‰ at 25-30 cm, suggesting progressive incorporation of C4 corn signature into MAOC at depths even in the plough horizon. The C/N ratios in MAOC was higher than C/N ratios in bulk SOC, also suggesting that MAOC was mostly plant-derived C. In summary, the degrees of deviations in plough horizon from long-term trend of soil $\delta^{13}C$ profiles suggest the various intensity of impacts of corn cultivation on SOC, both temporally along the soil profiles and geographically across black soils region in Northeast China. Natural $\delta^{13}C$ analysis is a powerful tool to quantify the contribution of crop residues into different carbon fractions and potentially provides important insights into the preservation of SOC and conservation of black soils.

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# Soil carbon dynamics and microbial associations across the soil profile under regenerative management in Northern California vineyards

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**ABSTRACT**

Regenerative agriculture (RA) practices are increasingly promoted to enhance soil health and carbon (C) sequestration in agricultural systems, yet their effectiveness is often evaluated using surface soil measurements that overlook processes occurring at depth. In perennial cropping systems such as vineyards, deep soil layers represent a substantial but poorly characterized component of soil organic carbon (SOC) storage, where interactions among soil physicochemical properties, microbial communities, and management practices may govern long-term C stabilization. This study investigates soil C dynamics and microbial associations across the soil profile in Northern California vineyards to establish a baseline framework for evaluating management impacts on SOC. We sampled soils to 1-m depth in three cover-cropped vineyards, collecting samples at 0-15, 15-30, 30-60, and 60-100 cm. Baseline measurements included particulate organic carbon (POC), mineral-associated organic carbon (MAOC), dissolved organic carbon (DOC), and microbial biomass carbon (MBC), alongside soil physicochemical properties. Bacterial community composition was characterized using 16S rRNA gene amplicon sequencing to examine associations between SOC pools and microbial structure along soil depth gradients. Baseline results show strong vertical stratification of SOC pools, with increasing dominance of MAOC in subsoil layers, highlighting the importance of subsurface processes for long-term C storage. Bacterial community composition varied systematically with soil depth and was closely associated with changes in soil properties and SOC pool distribution, indicating that microbial organization is an important component of depth-dependent C dynamics. In parallel, a short-term RA assessment incorporating no-till and sheep-grazing practices was established in one vineyard. Ongoing analyses are evaluating how two years of RA management influence soil physicochemical properties, SOC pool distribution, and bacterial and fungal community structure across soil depth. By integrating completed baseline observations with emerging management-focused assessments, this work aims to improve our understanding of how land use and regenerative practices shape soil C dynamics across entire soil profiles in vineyard systems. These insights will contribute to more comprehensive evaluations of SOC sequestration potential and inform management strategies aimed at improving soil function and resilience under Mediterranean-climate conditions.

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# Temporal Dynamics of Soil Organic Carbon Fractions and Microbial Activity Across a Chronosequence of Abandoned Paddy Fields in Korea

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**ABSTRACT**

Globally, farmland abandonment is increasing, with the cessation of rice cultivation being particularly pronounced in East Asia. Previous studies have shown that soil organic carbon (SOC) in abandoned paddy fields declines during the early stages of abandonment but tends to reaccumulate over the long term. This initial SOC loss is attributed to enhanced microbial decomposition following the shift from flooded to aerobic conditions, leading to depletion of both free particulate organic carbon (fPOC) and occluded particulate organic carbon (oPOC), as well as mineral-associated organic carbon (MAOC), traditionally regarded as a stable carbon pool. However, how SOC fraction dynamics are linked to soil microbial characteristics in abandoned paddies remains poorly understood. This study aimed to elucidate the temporal dynamics of SOC fractions along a chronosequence of abandoned paddy fields and their relationships with microbial activity and abundance. We investigated 13 abandoned paddy fields in central Korea (2–39 years since abandonment), along with seven cultivated paddies and ten adjacent forest sites as controls (30 sites total). Soil samples were fractionated into fPOC, oPOC, and MAOC, and their relative distributions and stocks were quantified. Microbial characteristics were assessed through measurements of enzyme activities related to carbon (C) and nitrogen (N) cycling and by quantifying bacterial and fungal abundance. SOC stocks initially declined following abandonment but gradually recovered over time, reaching levels comparable to cultivated paddies after approximately 12 years using the equivalent soil mass (ESM) approach and 17 years using the fixed-depth method. Among SOC fractions, oPOC showed a sharp initial decline followed by a slower-than-expected recovery, indicating high sensitivity to microbial decomposition. In contrast, MAOC exhibited notable temporal variability despite its presumed stability. Changes in the oPOC/MAOC ratio closely tracked oPOC dynamics, highlighting significant shifts in SOC composition during abandonment. Future work will expand the chronosequence by incorporating additional abandoned paddy fields from other regions, particularly targeting underrepresented abandonment periods, to further clarify microbial-mediated SOC stabilization processes during long-term paddy abandonment.

**Acknowledgments**

This work was also supported by Korea Environment Industry & Technology Institute (KEITI) through Project for developing an observation-based GHG emissions geospatial information map, funded by Korea Ministry of Climate, Energy, and Environment (MCEE) (RS-2023-00232066). This research was conducted using the database and analytical results of the 2025 Gyeonggi-do Climate Platform.

# Impact of Blast Furnace Slag-Based Enhanced Rock Weathering Alters Soil Organic Carbon Dynamics through Microbial Activity

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**ABSTRACT**

Understanding carbon cycling in urbanization-induced fragmented ecosystems requires a dynamic approach that captures carbon fluxes rather than static storage indicators. According to previous studies, microbial biomass carbon (MBC) serves as an active carbon pool that drives organic matter decomposition and nutrient transformation. Particularly, the ratio of MBC to soil organic carbon (MBC/SOC) represents carbon bioavailability and has been proposed as a key indicator that responds sensitively to environmental disturbances and provides early signals of ecosystem functional changes. Nevertheless, existing research on urban fragmented ecosystems has primarily focused on quantitative changes in SOC, insufficiently addressing how fragmentation-induced landscape characteristics such as physical boundaries and adjacent land uses influence MBC/SOC dynamics. Therefore, this study aimed to examine the effects of physical boundaries and adjacent land use types on SOC content and MBC/SOC in forests and grasslands fragmented by urbanization. We analyzed SOC and MBC/SOC in topsoil (0-15 cm), comparing edge (≤30 m) and interior (>30 m) zones of urbanization-fragmented forests and grasslands. The results revealed distinct carbon storage and utilization strategies between the two ecosystems. Forests exhibited high SOC content but low MBC/SOC, suggesting that carbon is stored in a physicochemically stabilized state with limited microbial accessibility. In contrast, grasslands showed low SOC content but high MBC/SOC, indicating a carbon system with a high proportion of active carbon pool and elevated biological turnover rates. Notably in forests, edge effects did not significantly alter total SOC, but MBC/SOC was significantly reduced at road-adjacent edges, suggesting that road proximity impairs active carbon pool formation. This study demonstrates that assessing carbon cycling in urbanization-fragmented ecosystems requires integrated consideration of not only SOC storage but also microbial-mediated carbon cycling indicators that reflect urbanization-induced fragmentation characteristics. Future studies will integrate soil respiration data to verify if the observed alterations in MBC/SOC at urban edges result in actual carbon losses.

**Acknowledgments**

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# Initial organic carbon content controls the depth-dependent soil organic carbon responses to liming

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**ABSTRACT**

Lime addition, widely advocated to alleviate soil acidity and promote plant growth in acidic soils, can influence soil organic carbon (OC) turnover by multiple mechanisms, including fostering soil aggregation, disrupting OC-mineral association, and indirectly increasing C inputs. Due to the interplay of competing processes, the net impact of liming on soil OC remains debated. To clarify the generalizable impact of lime application on soil OC across the soil profile and to decipher the underlying mechanisms, we combined a global meta-analysis of field observations with microcosm experiments across two soil types. Our results show that, overall, lime application increased soil OC by 5.7%, primarily through enhanced plant C inputs and associated increases in particulate organic carbon ($r = 0.77$). This effect, however, depended on both initial OC content and soil depth. Specifically, in OC-poor topsoil (OC<20 g/kg), liming enhanced the destabilization of particulate organic carbon and increased dissolved OC content. This process stimulated both OC decomposition and microbial necromass formation, yet the subsequent interaction between microbial-derived OC and mineral was inhibited, as elevated $OH^-$ competed with organic ligands for reactive mineral binding sites. Nevertheless, this negative effect was offset by increased C inputs due to enhanced plant growth, resulting in a net increase in topsoil OC (7.7 %). Within OC-rich subsoils (OC≥20 g/kg), lime application also destabilized OC and accelerated its decomposition. However, due to the inherently low microbial carbon use efficiency in the subsoil, microbial necromass production did not increase proportionally. Given the declining plant C inputs with depth, the enhanced C outputs — primarily as $CO_2$ — dominated the C turnover, leading to a net OC loss of approximately 5%. Our findings underscore that the loss of persistent subsoil OC should be carefully considered in the development of land management strategies aimed at maintaining or increasing soil OC, particularly while promoting the use of alkaline amendments for atmospheric $CO_2$ removal.

**Acknowledgments**

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# Trade-offs between soil organic carbon input and mineralization driven by high-level phosphorus fertilization: 30-year field evidence

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## ABSTRACT

The role of phosphorus (P)-fertilization in soil organic carbon (SOC) sequestration is critical yet paradoxical, as its impact on both carbon input and loss remains inadequately quantified. Through a 30-year paddy field experiment, we demonstrated that long-term high-level P-fertilization creates a significant trade-off between SOC accumulation and mineralization. While P-fertilization increased total SOC by up to 24.3%, this gain was driven exclusively by the accumulation of particulate organic carbon (POC) from enhanced plant-derived inputs. Conversely, the mineral-associated organic carbon (MAOC) pool, crucial for long-term stability, decreased by 6.5%. Phosphate anions competitively occupied binding sites on iron (Fe) oxides, as evidenced by a significant decrease in active Fe and a spatial decoupling of C and P at the microscale. This competition directly constrained MAOC formation. Furthermore, high-level P-fertilization accelerated SOC mineralization, increasing $CO_2$ emissions by up to 46.7%. This was mechanistically explained by a broad stimulation of microbial extracellular enzymes (both hydrolytic and oxidative) and a reduction in microbial carbon use efficiency. Consequently, the net ecosystem carbon balance peaked at an optimal P-fertilization level, beyond which the carbon costs from increased emissions and fertilizer production outweighed the gains. Our findings reveal that high-level P-fertilization directs carbon into a vulnerable, rapidly-cycling POC pool at the expense of a stable MAOC pool, challenging its efficacy for sustainable carbon sequestration. Based on these findings, precision P management was advocated to optimize the trade-off between productivity and stable SOC storage in agroecosystems.

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# Soil organic carbon stocks under no-tillage on farms in European Russia

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**ABSTRACT**

Conservation practices in agriculture can aid in carbon sequestration and contribute to the 4 per mille initiative. No-tillage is a promising practice to enhance carbon storage in soil compared to conventional tillage. It has shown its effectiveness in field experiments, but there is limited data supporting the justification of no-tillage on a farms scale due to the complex assessment of interacting factors in space and time. The research aims to evaluate the rate of carbon stock accumulation and forecast its dynamics using no-tillage (NT) versus conventional tillage (CT) in farms in three regions of European Russia. The farms were selected in Samara (Haplic Chernozems) and Rostov (Calcic Chernozems) regions, which have non-waterlogged landscapes, as well as in the Krasnodar region (Stagnic Chernozem), which has a periodic waterlogged landscape. In 2022-2023, we selected three adjacent fields at each site: one with CT, and two with NT for 5–14 years. At each field 30 sampling points were selected using a conditioned Latin hypercube design, taking into account variations in both spectral and terrain characteristics of the landscape. The soil samples were selected from the top (0-10 cm) and subsoil (10-30 cm) layers at each point (a total of 270 soil samples). Soil bulk density was determined at each point. The total carbon (TC) and inorganic carbon (IC) contents were analyzed to calculate soil organic carbon (SOC) content. Finally, the soil SOC stocks were calculated. In 83% of cases, it was observed that SOC stocks increased under NT compared to CT in the topsoil. This effect was observed due to an increase in both SOC content and bulk density. The accumulation rate of SOC stocks for NT was evaluated from 0.15 to 1.12 Mg $ha^{-1}$ $yr^{-1}$. In the subsoil, the SOC under NT decreased in 50% of cases, while in other cases it remained basically unchanged compared to CT. Using DNDC model, the long-term dynamics of SOC stocks were forecasted from 2023 to 2100 years, considering the SSP2-4.5 and SSP5-8.5 climate change scenarios in the Samara and Krasnodar regions. In the first 30 years of using the NT, the rate of SOC accumulation in topsoil (from 0.19 to 0.26 Mg $ha^{-1}$ $yr^{-1}$) will exceed its losses in the subsoils (from 0.06 to 0.12 Mg $ha^{-1}$ $yr^{-1}$) for the farm fields in two regions. However, in the following 50 years (2051–2100), the trend will reverse: SOC losses from the subsoil will exceed its accumulation in the topsoil by 1.1–2.6 times. Therefore, the development of technologies is necessary to enhance and preserve soil carbon in subsoils under NT practices. Here, it could be considered incorporating perennial cover grasses into crop rotations to enhance rhizodeposition.

The research was supported by the state assignment of the Ministry of Science and Higher Education of the Russian Federation No. 125061107005-4.

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# Effects of Historical Land Use Changes on Deep Soil Carbon, Nitrogen and Microbial Communities in Alpine Sandy Region

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## ABSTRACT

Land use change is a key driver of soil carbon and nitrogen dynamics, significantly influencing soil fertility. However, the effects of historical land use changes on deep soil carbon and nitrogen dynamics, as well as microbial community composition in alpine sandy regions, remain poorly understood. This study examined a 23-year-old *Caragana microphylla* shrub forest in the Gonghe Basin, comparing carbon and nitrogen dynamics, as well as microbial community characteristics, across the 0-500 cm soil depth in historically afforested farmland forest (FF), planted forest (PF), and mobile dunes (CK). The study area is located at an elevation of 2,871 to 3,870 meters above sea level, with an annual mean temperature of 3.9°C and average annual precipitation of 246.3 mm, primarily occurring between May and September. The annual mean potential evaporation is 1,716.7 mm, resulting in an exceptionally arid climate. This region is classified as an alpine arid zone, with predominantly sandy soils. The results demonstrated that historical land use changes significantly influence the content and storage of soil organic carbon (SOC), inorganic carbon (SIC), and total nitrogen (STN). Across the 0-500 cm soil depth, average SOC, SIC, and STN concentrations were as follows: FF (2.40, 10.37, 0.28 g·kg$^{-1}$) > PF (1.46, 9.53, 0.17 g·kg$^{-1}$) > CK (0.89, 8.31, 0.11 g·kg$^{-1}$). Soil organic carbon, inorganic carbon (SIC), and total nitrogen storage at each 100 cm subsoil depth were as follows: FF (28.99-39.16, 132.92-149.48, 3.44-4.76 t·hm$^{-2}$) > PF (18.08-23.08, 128.27-139.39, 1.71-3.02 t·hm$^{-2}$) > CK (12.97-14.39, 123.82-130.29, 1.69-1.76 t·hm$^{-2}$). Soil water content is a critical environmental factor influencing deep soil carbon and nitrogen cycling in alpine sandy regions. Soil microbial community diversity was highest in the 0-40 cm surface layer under FF, whereas PF exhibited greater diversity in the 100-500 cm deeper layer. Soil bacterial communities were more sensitive to historical land use changes than fungal communities. In CK, soil microbial communities were primarily influenced by nitrogen and physical factors, while in PF, soil organic carbon and total nitrogen were the principal influencing factors. In FF, soil bulk density and water content were the key determinants. In summary, the FF model in alpine sandy regions outperforms the PF model in enhancing soil SOC, SIC, and STN content across the 0-500 cm layer and promoting surface microbial diversity. Conversely, the PF model plays a unique ecological role in maintaining deep soil microbial diversity. Therefore, attention to the long-term effects of historical land use transitions is crucial for advancing the sustainable development of desertification prevention and control efforts.

**Key Words:** alpine sandy region; historical land use types; soil organic and inorganic carbon; soil total nitrogen; soil microbial diversity

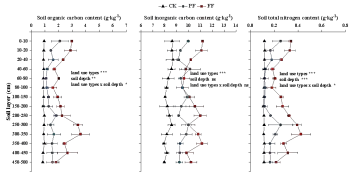


**Fig.1 Soil organic carbon, inorganic carbon, and total nitrogen content in the 0-500 cm soil depth of 23-year-old *C. microphylla* shrublands planted on different historical land use types**

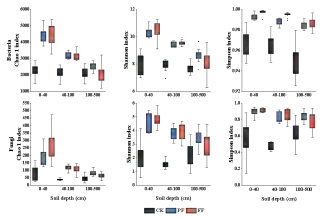


**Fig.2 Soil microbial α-diversity in the 0-500 cm soil depth of 23-year-old *C. microphylla* shrublands planted on different historical land use types at the phylum level**

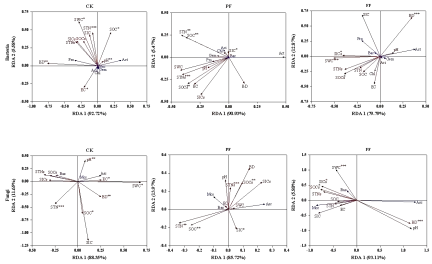


**Fig.3 RDA and Monte carlo test of key soil microbial richness and physicochemical properties across different historical land use types at the phylum level**

*****:*P*<0.001,**:*P*<0.01,*:*P*<0.05**

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# Modeling of carbon sequestration in future climate conditions in a long-term field experiment on light-textured Retisol in the Tver Region, Russia

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**ABSTRACT**

Soil is a potential sink for greenhouse gases. The possibility of accumulation of soil organic carbon (SOC) in arable soils requires accurate consideration of interactions between climate, soil, and farming systems. This task can be solved by modeling the dynamics of SOC stocks based on data from long-term field experiments.

SOC dynamics in a long-term field experiment with mineral and organic fertilization on sandy loam Retisol in Tver Region, Russia, was traced with the dynamic SOC model RothC from the launching the experiment (1956) until the present. The initial SOC content in the studied soils was about 30 t/ha. During the observation period, C stocks decreased by 10-34% compared to the initial level, depending on the fertilization system and quantity of fertilizers applied. The model was also used to forecast SOC changes up to 2090 and to assess the prospects for different agricultural techniques in increasing SOC stocks for the two contrasting climatic scenarios (RCP4.5 and RCP8.5) and the two economic scenarios (implying changes in crop rotations and fertilizer rates). Up to 2090, steady growth of SOC stocks is expected in all the compared treatments for both scenarios.

The possibility of application various organic fertilizers and alternative methods of soil cultivation as additional approaches to the accumulation of SOC has been studied. It is shown that if existing technologies are maintained in the conditions of the future climate, the increase in SOC stocks in the arable layer (0-20 cm) of the studied soils by 2090 can amount from 19% (RCP8.5) up to 34% (RCP4.5) of the initial content, and the implementation of carbon-saving technologies can provide an additional increase of more than 19%. Among the alternative sources of organic fertilizers, the best result can be expected with compost and peat mixtures application. Both fertilizers can provide additional accumulation of SOC up to 8 t/ha by 2090 (over 70 years) compared with the use of FYM, while the use of green-manure fallow and minimal tillage cannot be considered as optimal strategies, since these techniques lead to a slower SOC accumulation compared to FYM.

It is shown that the studied soils have a significant potential for carbon sequestration, since its consistent accumulation can occur even for business as usual scenario with maintaining the field practices of the initial treatments. However, proper SOC management makes it possible to achieve a significantly greater increase in carbon stocks.

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# Effects of 50-year long-term land-use and management changes on soil C and N stocks and their stable isotope ratios at the Yamagata University Farm, Japan

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## ABSTRACT

Carbon (C) and nitrogen (N) are essential soil components that drive fertility, regulate nutrient cycling, and influence the stability and productivity of agricultural ecosystems. Land use and management change (LUMC) influence the distribution and stability of C and N pools in the soils. Shifts from rice paddies to aerobic conditions alter organic matter inputs, decomposition rate, and isotopic composition, such as the soil stable isotope ratio ($\delta^{13}C$ and $\delta^{15}N$), reflecting transformations in C and N sources and cycling processes. The more labile or easily decomposable, fractions such as hot water or water-extractable organic C (HWEOC or WEOC) and N (HWEON or WEON) are critical for rapid nutrient turnover and microbial activity and are sensitive to changes in land use and management practices; because water-extractable fractions represent the more bioavailable forms of C and N, their concentrations tend to respond quickly to environmental changes. This study examined the effects of long-term land-use and management change from rice paddy to orchard (apple and chestnut), upland (soybean, wheat, etc.), and pasture (reed canary grass) on soil organic C (SOC) and total N (TN) contents, including their $\delta^{13}C$ and $\delta^{15}N$, and the concentrations of HWEOC/N or WEOC/N. Soil samples were collected in November 2024 from the surface (0–15 cm) and sub-surface (15–30 cm) layers across four distinct land types at the Yamagata University Farm, Northeast Japan, where the LUMC occurred 50 years ago from 1974. Samples were air-dried, homogenized by grinding, and passed through a sieve prior to analysis. Air-dried soils were used to measure SOC and TN contents and calculated for SOC and TN stocks, and stable isotope ratios for C and N were determined. To extract labile form of organic C and N, soils were mixed with water at a 1:5 ratio. HWEOC/HWEON were obtained by extraction at 80°C for 16 hours, whereas WEOC/WEON were extracted at room temperature. Following filtration, the extracts were divided into two portions: one for the analysis of C and N concentrations, and the other was freeze-dried for subsequent stable carbon isotope ratio analysis. The results demonstrate that LUMC significantly affects SOC and TN contents. Conversion from the original paddy rice (used as a control) to aerobic land uses significantly reduced SOC content at the 0-30 cm soil depth by 33.3%, 45.8%, and 47.9% in pasture, orchard, and upland soils, respectively. Similarly, TN content was highest in the paddy rice soil at 4.0 g $kg^{-1}$. It decreased to 3.2 g $kg^{-1}$ in pasture soil ($P$ <0.05), and to 1.6 g $kg^{-1}$ and 1.3 g $kg^{-1}$ in orchard and upland soils, respectively ($P$<0.05). SOC stock at 0-30 cm depth was highest in rice paddy soils (6.74 Mg C $ha^{-1}$), followed by pasture (5.93 Mg C $ha^{-1}$) and upland (5 Mg C $ha^{-1}$) soils, and lowest in orchard soils (4.86 Mg C $ha^{-1}$). TN stocks were greatest in pasture soils (0.59 Mg N $ha^{-1}$), but did not differ significantly from rice paddy soils (0.57 Mg N $ha^{-1}$), whereas upland and orchard soils had significantly lower values (0.47 and 0.45 Mg N $ha^{-1}$, respectively). Statistically significant differences among land-use types indicate substantial reductions in both SOC and TN in orchard and upland soils compared with rice paddy and pasture soils, suggesting depletion of C and N stocks following conversion of paddy rice to aerobic land uses, particularly to orchards. The lowest soil $\delta^{13}C$ (-27.60‰) and $\delta^{15}N$ (0.93‰) values in paddy rice soils, relative to aerobic land uses, reflect the impacts of anaerobic conditions on C and N cycling processes such as suppressed nitrification and enhanced denitrification. Soil C and N contents showed strong correlations with the water-extractable fractions, regardless of extraction temperature. We conclude that the conversion of rice paddies to aerobic land uses significantly decreased the soil C and N stocks within the 0-30 cm layer and affected soil fertility and climate change.

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# Chemical carbon sequestration dominates leguminous green manure return, whereas physical carbon sequestration prevails in non-leguminous systems

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## ABSTRACT

Soil organic carbon (SOC) is fundamental to agricultural sustainability, yet intensive practices have depleted global SOC stocks by 25-75%. Leguminous green manure (LCS) enhances carbon input via biological N2 fixation, while non-leguminous green manure (NLCS) primarily improves physical protection through soil aggregation. The distinct carbon sequestration pathways of these two green manure types require systematic evaluation for optimized soil carbon management. A global meta-analysis of l586 paired observations from 2l0 studies (l990-2022) quantified LCS/NLCS impacts on SOC fractions. Data from Web of Science and CNKI were analyzed using random-effects models. Key variables included POC (particulate organic carbon), MAOC (mineral-associated organic carbon), and total SOC, with moderators encompassing climate (MAT-mean annual temperature/MAP-mean annual precipitation), soil properties (pH/texture), and agronomic practices (N fertilizer rate/tillage) et al. LCS increased POC (+27.95%), MAOC (+7.2%), and total SOC (+9.4l%) through chemical pathways (N-enhanced organic matter input). NLCS predominantly enhanced MAOC (+l2.3%) via physical mechanisms (improved soil aggregation). Climate effects revealed MAT >l5°C and MAP >l000mm amplified POC sequestration, while MAOC responses were soil-specific. Acidic soils (pH<6) and fine textures (clay>40%) favored MAOC increases. Optimal N rates (0-l20 kg ha_1) and reduced tillage maximized carbon benefits, with LCS showing stronger labile carbon accumulation than NLCS. LCS exhibits chemical-dominated carbon sequestration, while NLCS demonstrates physical-dominated mechanisms. This pathway divergence necessitates site-specific green manure selection. Climate-soil-management interactions must be considered to optimize carbon sequestration. The findings provide actionable strategies for enhancing agricultural carbon sinks and advancing sustainable farming practices under climate change scenarios, with implications for global carbon neutrality targets.

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# Beyond Methane: Reassessing the Role of Rice Paddies in Global Warming

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**ABSTRACT**

As a major cereal crop, the global demand for rice continues to increase. However, the expansion of rice cultivation is constrained by substantial methane ($CH_4$) emissions during flooded rice cultivation. Since various soil management practices have been developed to mitigate $CH_4$ emissions, and rice paddies have high potential for soil carbon (C) sequestration, the impact of rice cropping systems on global warming requires re-evaluation. To compare the effects of cropping on global warming between rice paddy and maize upland systems, the net global warming potential (GWP) was evaluated by integrating $CH_4$ and nitrous oxide ($N_2O$) fluxes and changes in soil organic C (SOC) stocks under identical fertilization regimes. During crop cultivation, net GWP in rice paddies was predominantly driven by $CH_4$ flux, whereas in upland fields it was strongly influenced by SOC stock depletion. Under conventional fertilization (NPK and green manure), net GWP was substantially higher in rice paddies than in upland systems; however, under biochar application, the climatic impact was markedly lower. Moreover, the combined application of $CH_4$ mitigation practices, including mid-season drainage, reduced the net GWP of paddy fields to levels considerably lower than those observed in upland fields. A similar trend was observed for greenhouse gas intensity (GHGI), which indicates the net GWP per grain productivity. Consequently, if $CH_4$ mitigation practices for rice paddies are effectively implemented, rice could be produced in a more climate-friendly manner than in upland systems.

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# Tree proximity effects on soil organic carbon, bulk density and soil moisture in a dryland landscape

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## ABSTRACT

Tree-based farming systems are widely promoted to enhance soil fertility and sequester carbon, yet fine-scale empirical evidence from semi-arid agroecosystems remains limited. Here we quantify how individual trees modify soil physical, chemical and hydrological properties in a Mediterranean dryland landscape. Soils were sampled around 14 individual trees representing four contrasting lineages (Cupressaceae, Pinaceae, Myrtaceae and mallee species; scenarios S1–S4) using a nested depth–distance design (0–5, 5–10, 10–20 and 20–30 cm at 1, 2, 4 and 8 m from trunks). We measured bulk density, gravimetric moisture, soil organic carbon (SOC), total nitrogen (TN), mineral nitrogen ($NH_4^+$-N, $NO_3^-$-N) and Colwell P. Effects of depth and distance were tested using linear mixed-effects models. Across scenarios, SOC and nutrient pools were consistently elevated beneath canopies, with the strongest enrichment typically within 1–2 m of trunks and in surface mineral soil (0–10 cm; 0–5 + 5–10 cm combined), forming spatially confined fertility islands. Bulk density increased with depth and distance from trees; for example, in the 10–20 cm layer, average bulk density was ~1.07 g $cm^{-3}$ at 1–2 m versus ~1.25 g $cm^{-3}$ at 8 m. Importantly, soil moisture did not decline near trees: in the upper 0–20 cm, gravimetric moisture averaged ~10–12% at 1 m compared with ~8–10% at 8 m, while differences largely disappeared at 20–30 cm where soils were near field capacity (~15%). Partial redundancy analysis showed that soil depth was the dominant structuring factor (explaining 85–95% of variance), with distance from trees representing a weaker but consistent secondary gradient aligned with SOC and nutrient enrichment. Together, these results demonstrate that scattered trees can enhance near-surface carbon storage, nutrient availability and soil structure without an apparent moisture penalty in this dryland system, supporting strategic tree integration as a pathway for climate mitigation and soil restoration.

# Land use effects on soil carbon retention through glomalin-mediated aggregation

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**ABSTRACT**

The glomalin-related soil protein (GRSP), produced by arbuscular mycorrhizal fungi, plays a critical role in soil organic carbon (SOC) storage and stabilization across terrestrial ecosystems. We examined the effects of four contrasting land-use types (bare land, cropland, grassland, and woodland) originating from the same soil matrix on GRSP dynamics, soil aggregation, and SOC accumulation. We found that grassland and woodland ecosystems exhibited significantly higher contents of macroaggregates (>0.25 mm), SOC, total nitrogen (TN), total GRSP (TG), easily extractable GRSP (EEG) and aggregate stability compared with cropland and bare land. Across all land uses, the EEG/SOC and TG/SOC ratios in Mi and SC were higher than other aggregates sizes. Correlation analyses showed that TG was significantly and positively correlated with SOC in bulk soil and macroaggregates (>2 mm), while EEG exhibited significant positive correlations with SOC in smaller macroaggregates and microaggregates. Furthermore, GRSP was strongly and positively correlated with aggregate stability, and the content of TG and the TG/SOC ratio were mainly influenced by microbial biomass carbon (MBC) and SOC. Our findings highlight the contrasting correlations of TG and EEG to SOC storage across aggregate size classes, with TG playing a more prominent role in bulk soil and large macroaggregates, and EEG more significantly associated with SOC accumulation in small macroaggregates and microaggregates. This study advances our understanding of the mechanisms by which GRSP facilitates SOC sequestration and soil aggregate formation under different land-use regimes, informing sustainable land management strategies for climate change mitigation.

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# Demonstration and application of zero-carbon Taoyuan biochar carbon sequestration technology

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**ABSTRACT**

The Zero-Carbon Peach Orchard Demonstration Project in Fu'an applies biochar-based carbon sequestration technology to establish a low-carbon, high-efficiency agricultural model. Agriculture contributes 10–12% of global anthropogenic greenhouse gas emissions—mainly methane ($CH_4$), nitrous oxide ($N_2O$), and $CO_2$—yet it remains one of the few sectors capable of transforming from a net carbon source into a net carbon sink. Biochar, a negative-emission technology produced via pyrolysis of agricultural and forestry biomass under oxygen-limited conditions, contains highly stable carbon structures with residence times ranging from centuries to millennia. When introduced into soils, biochar enhances long-term carbon storage while improving soil fertility, water retention capacity, pH balance, nutrient availability, and microbial activity.

Fu'an City possesses abundant biomass resources and soils with strong carbon sequestration potential. The project implements biochar soil amendment in a peach orchard located in Hutu Village, the core production area of Muyang honey peaches. A one-year field experiment includes three treatments: an unfertilized control, a conventional fertilization plot, and a biochar-amended plot with equivalent fertilizer inputs. Soil samples collected at multiple depths and seasonal stages—following national sampling standards—are analyzed for pH, organic matter, nutrients, total carbon, bulk density, moisture, salinity, heavy metals, and GHG-related parameters. Peach tree growth, yield, and fruit quality indicators (size, sugar content, acidity, firmness, vitamin C, and heavy metals) are also monitored.

The project also establishes a green technology evaluation framework and conducts a full lifecycle carbon footprint assessment of peach production. Using ISO 14040/14044 and ISO 14067 standards, carbon emissions from resource inputs, cultivation, and harvesting are quantified based on localized data and IPCC emission factors. Outputs include a Green Technology Evaluation Certificate, a Product Carbon Footprint Report, and carbon-neutrality verification for the orchard. The project ultimately provides a replicable methodology for low-/zero-carbon orchard development, offering data-driven guidance for resource efficiency, emission reduction, enhanced carbon sinks, and sustainable agricultural modernization in Fu'an.

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# A model-based tool for supporting sustainable management of soil organic carbon in Swiss croplands

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**ABSTRACT**

Soil organic carbon (SOC) is central to soil health and the global carbon cycle, as it represents the largest terrestrial carbon pool. SOC stocks are strongly affected by agricultural management. Unsuitable management often leads to SOC loss and soil degradation, while adapted management sustains or enhances SOC content in agricultural soils. Understanding and quantifying the impact of management on SOC dynamics is therefore critical for agricultural sustainability and climate mitigation. Here, we present results of a biogeochemical model-based tool to estimate the effects of farm management on long-term SOC stock dynamics in Swiss croplands under varying management actions and climate scenarios. The tool integrates well-established models, such as RothC, DayCent and AMG, and was calibrated using long-term management and SOC measurement data from the Swiss Soil Monitoring Network (NABO) and field trials. By combining multiple national datasets, including information on soil properties, weather conditions, land use types, and manure management, the tool reduces the data input requirements for users. The resulting platform will be designed to enable field-scale simulations of SOC stock dynamics, offering farmers, advisors, and policymakers a science-based tool to evaluate the influence of management options on soil health. The overarching goal is to promote sustainable soil management and support national agricultural objectives.

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# Effects of tillage practices on environment, energy, and economy of maize production in Northeast China

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**ABSTRACT**

Conservation tillage plays a positive role in restoring degraded cropland in terms of increasing carbon sequestration, improving soil aggregation, and maintaining crop productivity. Assessing the key indicators of environment, energy, and economy under different tillage practices could provide a comprehensive scientific basis to implement low-carbon emission, clean and sustainable agricultural management, especially in the long-term experiment field. Our objectives were: 1) to compare crop production under different long-term tillage practices, 2) to evaluate the carbon footprint (CF), energy budget, and net ecosystem economic benefit (NEEB) of spring maize production under different long-term tillage practices. Three tillage practices consisting of conventional tillage with complete removal of residue (CT), moldboard plowing with residue return (MP) and no-tillage with residue return (NT), had been conducted for eight years. Greenhouse gas (GHG) emissions from the soil were measured, and the inputs of raw materials and outputs of crop production were also recorded. CF, energy budget, and NEEB were evaluated for two consecutive growing seasons based on the life cycle assessment (LCA) approach. Compared with CT, NT could reduce $N_2O$ emissions and absorb more $CH_4$, whereas MP significantly increased $CO_2$ emissions from soil. However, there was no significant difference in maize yield among all treatments. Moreover, NT led to both the lowest GHG emissions from soil (GWPGHG) and agricultural inputs (AIGHG), thus NT decreased CF by approximately 40% compared to CT for maize production. Furthermore, MP and NT decreased 8.4% and 35.7% of the energy inputs owing to lower diesel fuel consumption in comparison with CT, yet there was no significant difference in energy output among different tillage practices. The same was true in NEEB, although MP and NT showed lower investments during maize production. These results indicated NT required the lowest energy and financial investment for the same maize yield. In conclusion, NT could minimize CF and energy inputs while insuring maize production from a long-term perspective. Long-term NT can be implemented in Northeast China and similar agro-eco-regions around the world. The findings of our study provide scientific data on the performance of different long-term tillage practices in the environment, energy budget and economic benefits.

# Exogenous organic carbon-induced stoichiometric balance stimulates microbial high growth potential yield strategies to promote necromass accumulation in soil carbon pools

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**ABSTRACT**

Understanding the microbial transformation of exogenous organic carbon (EOC) into persistent soil organic carbon is paramount for mitigating climate change. While microbial necromass carbon (MNC) is a key stable carbon pool, the mechanisms governing its accumulation under EOC inputs remain elusive. To address this, we integrated a global meta-analysis of 400 paired observations with an eight-year field experiment and metagenomic sequencing. Our meta-analysis revealed that EOC inputs significantly enhanced soil MNC by 38.13% and increased its contribution to the total soil organic carbon pool by 5.24%. Amendment type was a critical regulator, with low C/N manure inducing a greater MNC increase (up to 75.17%) than high C/N plant residues. Field data robustly validated these global trends: compared to the control, composted sheep manure (C/N=14.1) and wheat straw (C/N=64.6) elevated total MNC by 39.6% and 26.4%, respectively. We identified that EOC-induced alleviation of soil stoichiometric imbalance (C/N-imbalance index shifting towards 1) was the universal driver, promoting a community-wide shift towards a high growth potential yield (Y) strategy. Metagenomic dissection uncovered two quality-dependent metabolic gateways: 1) High C/N straw sustained a mild C/N imbalance, forcing a costly "Y+A" trade-off. This involved significant upregulation of flagellar assembly (A-strategy) for motility and nitrogen mining, coupled with cell division pathways (Y-strategy), ultimately favoring fungal necromass accumulation. 2) In contrast, low C/N manure achieved stoichiometric equilibrium, minimizing investment in resource acquisition. This facilitated a pure Y-strategy, channeling energy into biofilm formation and amino acid biosynthesis, which concurrently boosted both bacterial and fungal necromass. Importantly, the Y-strategy encompassed the highest number of unique genera (387), indicating evolutionary selection for growth-oriented taxa. Our study establishes a mechanistic paradigm where EOC quality, mediated by soil stoichiometric balance, steers microbial life-history trade-offs to dictate the pathway and efficiency of necromass carbon sequestration. We propose that tailoring organic amendments to foster Y-strategies offers a targeted, microbiology-based approach to optimize the 'microbial carbon pump' and enhance carbon sequestration in agricultural soils.

**Acknowledgments**

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# Management practices to mitigate long-term soil organic carbon losses in temperate arable soils

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**ABSTRACT**

Over the past decades, soil organic carbon (SOC) in agricultural soils has shown a decreasing trend across Europe, reflecting the combined effects of management practices and climate change. Long-term field experiments offer a unique opportunity to study these effects and identify management strategies that can mitigate SOC losses under changing climatic conditions.

This contribution combines results from two long-term experiments located at the same site in Puch/Fürstenfeldbruck, Southern Germany: a compost amendment experiment (1994–2023) and a management comparison experiment (IOSDV, 1983–2021) with varying organic matter inputs and mineral nitrogen fertilization rates. Both experiments revealed a distinct SOC content decline, coinciding with a marked regional temperature rise and increased frequency of drought–rewetting cycles. Despite continuous or even increasing organic inputs, SOC contents declined in most cases, indicating climate-driven acceleration of SOC mineralization. Across treatments, only management strategies combining multiple organic amendments (e.g., slurry, straw incorporation, and cover crops) or the application of compost can mitigate SOC loss to a certain extent. The results emphasize that improved management can buffer SOC losses and compensate enhanced decomposition processes under a warming climate.

The analysis of both long-term experiments highlights the necessity for improved agricultural management to mitigate SOC losses and maintain soil functionality in a rapidly changing climate.

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# Integrated carbon-nitrogen budget and cost-effective management in China

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**ABSTRACT**

Carbon and nitrogen are fundamental elements in global biogeochemical cycles, exerting critical influences on air and water quality, biodiversity, and human health. Over the past four decades, China has released substantial amounts of carbon and nitrogen into the environment, leading to significant regional and global consequences. To support effective monitoring and regulation, we developed a coupled human and natural systems (CHANS) model that quantifies national carbon-nitrogen budget and evaluates their ecosystem-level interactions from 1980 to 2020. During this period, carbon emissions increased by a factor of 6.5 and nitrogen emissions by a factor of 2.3. Our results show that integrated carbon and nitrogen management could reduce nitrogen pollution to air and water by up to 75% and lower carbon emissions by 91% by 2060. Relative to managing carbon or nitrogen in isolation, the integrated approach enables additional reductions of 1.8 million tonnes of nitrogen and 26.6 million tonnes of carbon by 2060. It also decreases the unit abatement cost by 37% and yields total societal benefits of US$1,384 billion. These findings underscore the necessity of coordinated carbon-nitrogen governance and offer a robust scientific basis for nature-based solutions, aligning with China's pursuit of net-zero carbon emissions and synergistic air and water quality improvements.

**Keywords:** Carbon cycle; Nitrogen cycle; Mitigation; Cost-benefit analysis; Nature-based solution

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# Blue Carbon Stocks in Brazilian Mangroves

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**ABSTRACT**

Mangroves are notable for providing diverse ecological functions and ecosystem services, including carbon (C) sequestration and climate change mitigation. In fact, these ecosystems, recognized as Blue Carbon Ecosystems, can store large amounts of C within living and dead biomass, but mostly on its soils due to the predominant anoxic/sub-oxic conditions and organo-mineral interactions that hampers organic matter decomposition. In this sense, Brazil holds the world's second largest area, covering approximately 8% of the total global mangrove area. However, since Brazil present a unique coastal zone conformation, spanning from northern hemisphere to subtropical latitudes, there is a wide variation in litho-climate conditions which controls C dynamics along Brazilian coast. Thus, the main goal of this work is to integrate C stock data across Brazilian mangroves, assessing variability of coastal compartments. Total Ecosystem C Stocks (TECS) were quantified, considering soil, above- and belowground stocks from mangrove areas in the Southeastern, Northeastern, and Amazon regions of Brazil. The aboveground biomass of evaluated Brazilian mangroves accumulated 5.82-254.95 Mg C per hectare (mean±SD = 73.3±68.07 Mg C per hectare), while the carbon stored in the soils, at depths up to 100 cm, was found to be between 13.2 and 405.5 Mg C per hectare (156.95±123.47 Mg C per hectare). The largest amounts of soil C stock were found along the Southeastern (332.16±74.79 Mg C per hectare) and Amazon (327.75±17.32 Mg C per hectare) coasts. Amazon region also showed the highest aboveground stock amount (170.50±16.26 Mg C per hectare). In contrast, the Northeastern coast presented mean soil C stock of 95±67.23 Mg C per hectare and an aboveground stock of 64.54±67.34 Mg C per hectare. These findings support prevailing research, showing that mangrove soils can store considerably more carbon than aboveground biomass, highlighting the role of the soil as an important blue carbon sink. The highest carbon stock rates were also observed in mature mangroves, recovered and under revegetation processes. Thus, conservation and regeneration efforts must prioritize the protection of mangrove soils to effectively mitigate the emission of greenhouse gases, such as carbon dioxide and methane, into the atmosphere.

**Keywords:** Brazilian coastal ecosystems, Total ecosystem C stocks, Greenhouse gases emissions.

**Acknowledgments:** CNPq, FAPESP, FAPERJ, CAPES.

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# Mangrove Biomass and Soil Carbon Stocks: Spatial Approach in the Cananéia Region

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## ABSTRACT

Mangrove forests are key Blue Carbon ecosystems due to their high primary productivity and exceptional capacity to store carbon in soils. However, extreme weather events threaten this ecosystem, particularly in previously impacted or degraded areas. This study examines the relationship between Gross Primary Productivity (GPP) and soil carbon content in pristine and degraded mangroves within the Cananéia-Iguape Coastal System (São Paulo, Brazil). Soil samples were collected at multiple depths and analyzed for pH and redox potential (Eh), and organic carbon content. In parallel, GPP was estimated using MODIS products (MOD17A2H and MOD13Q1), enabling a temporal assessment of vegetation dynamics from 2012 to 2023. Results show that the degraded mangrove exhibits markedly lower soil carbon content and lower Eh values (6.4 ± 0.4 mV) compared to the pristine mangrove. These conditions reflect intensified organic matter decomposition due to loss of vegetation and carbon inputs. In contrast, the pristine site maintains higher soil carbon content and Eh values (30.6 ± 21.8 mV), indicating a geochemically functional and expected geochemical environment. Remote sensing analysis further revealed persistently low vegetation vigor in the degraded area expressed by low EVI/NDVI and reduced GPP while the pristine mangrove sustained consistently higher productivity throughout the temporal record. Together, these results highlight how vegetation decline and soil carbon losses reinforce redox deterioration in degraded mangroves and underscore the value of integrating field and satellite indicators for effective conservation and management of these ecosystems. Ultimately, strengthening the monitoring and preservation of mangrove ecosystems is essential not only for maintaining local ecological functions, but also for safeguarding global climate stability and the well-being of human populations that depend on these critical Blue Carbon reserves.

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# Soil carbon fluxes as indicator of Healthy urban soils in a Mediterranean city

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**ABSTRACT**

Urban green areas provide major ecosystem services which are essential for the well-being of the most populated areas of the world. We hypothesized that the healthier the city, the better ecosystem services it provides. In this context, carbon dynamics could be used as indicators of soil health. Under a Mediterranean-type climate, carbon fluxes follow a pattern modulated by climate and vegetation type, and are influenced by a set of environmental and management factors. A set of plots (n=3) was selected across four types of vegetation (perennial and annual grassland, open-sized herbs of *Diplotaxis* sp., and meadow grassland of *Malva silvestris*) in four different urban green areas of Madrid. In each of the plots, an intensive monitoring programme of the soil carbon cycle was performed during 2023-2024, including: soil respiration, enzyme activities of the carbon cycle (α, β-Glucosidase, β-Galactosidase, Cellobiose, Phenoloxidase); Total Organic Carbon (TOC), hot and cold water soluble carbon fractions, microbial biomass, among other biological properties. Results show that climate (temperature and humidity) has a predominant effect on respiration rates, whereas vegetation type drives enzymatic activities. Moreover, perennial grasslands tend to accumulate more carbon than the rest of the vegetation communities, while the grassland of *Malva silvestris* shows a high rate of mineralisation.

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**Key words:** enzymatic activity, soil respiration, urban soils, Mediterranean

# Effects of crop rotation and organic amendments on crop productivity, soil chemical properties, and soil organic carbon accumulation in greenhouse vegetable systems

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## ABSTRACT

Soil organic carbon (SOC) accumulation is a key strategy for mitigating global warming. However, in Korean greenhouse horticulture, the combined effects of cropping system and organic amendment type on soil properties and SOC dynamics are poorly quantified. This study compared crop productivity, soil chemistry, and SOC stocks and fractions under fertilization regimes (chemical fertilizer, animal manure compost, and commercial organic fertilizer) combined with cropping systems (repeated cropping vs. crop rotation). The experiment was conducted from March 2023 to October 2025 in Anseong, Gyeonggi, Korea. Treatments comprised a chemical fertilizer control (CF), animal manure compost (AC), and a commercial organic fertilizer (OrF). The AC and OrF treatments were each managed either as a repeated-cropping system (RC) with continuous mustard greens or as a crop rotation system (CR) with mustard greens, spinach, and hairy vetch. RC involved two cropping cycles per year, and CR three cycles including hairy vetch as green manure/cover crop. Key soil chemical properties (pH, available P, exchangeable cations, total N, and SOM) differed markedly among treatments. Soil pH was particularly sensitive to amendment type, being lowest in OrF plots and suggesting acidification-related growth constraints. In 2025, mustard green yields were higher in CF and compost treatments (1,608.3–1,850.4 kg 10a$^{-1}$) than in OrF treatments (1,236.7–1,287.7 kg 10a$^{-1}$), with CF and AC forming a significantly higher-yielding group. Within each organic amendment type, rotation tended to outyield repeated cropping, indicating that hairy vetch–based rotation improved nutrient supply and organic matter inputs, although these differences were not statistically significant. SOC stocks increased in all treatments between 2023 and 2025. SOC stock in CF rose from 19.48 to 37.72 Mg C ha$^{-1}$ (+18.24 Mg C ha$^{-1}$). In organic-amended plots, SOC increased by 21.25 and 21.12 Mg C ha$^{-1}$ in RC-AC and RC-OrF, and by 34.02 and 36.76 Mg C ha$^{-1}$ in CR-AC and CR-OrF, respectively, giving organic-amended soils 6.8–16.1 Mg C ha$^{-1}$ more SOC than CF in 2025. The mineral-associated organic matter (MAOM) fraction, representing a relatively stable SOC pool, was similar in CF and OrF treatments (38.33–39.04 g kg$^{-1}$) but higher in compost treatments (47.36–51.23 g kg$^{-1}$), indicating that compost particularly promoted SOC stabilization in mineral-associated forms. Overall, combining animal manure compost with a crop rotation system including hairy vetch in protected horticultural soils maintained or exceeded conventional yield levels, mitigated soil acidification relative to sole application of commercial organic fertilizer, and enhanced SOC stocks and MAOM fractions over the medium term. These results show that integrated organic matter management via compost and diversified crop rotation can increase SOC storage and sustain soil functions, offering a practical strategy for carbon-neutral protected horticulture.

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# Permafrost ecosystems of Pur-Taz interfluve (Western Siberia) as a source of methane in the context of climate change

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**ABSTRACT**

Among greenhouse gases (GHG) whose concentrations in the atmosphere have been rising throughout industrial era, methane ($CH_4$) is the second most potent one for its contribution to global warming. Being low in absolute terms, $CH_4$ atmospheric content has increased by 260% since 1750. About a third of total $CH_4$ emissions comes from freshwater ecosystems where it is produced anaerobically by methanogens decomposing organic matter (Saunois et al., 2024).

Among the most waterlogged regions of the world, West Siberian Lowland (WSL) is characterized by vast reserves of frozen organic carbon in permafrost-affected tundra wetlands. As permafrost thaws due to accelerated (+0.5 ºC decade$^{-1}$ over 1965–2015 period) Arctic warming (NOAA), this carbon becomes entrained in the active layer (AL) and available for conversion to $CH_4$. Within WSL, low-Arctic tundra wetlands are the most vulnerable to climate change due to near-zero permafrost temperatures. As for Pur-Taz interfluve, where our study area was located, their vulnerability has been assessed through the prism of ecosystem changes. The key changes are the following:

1. lengthening of the growing season by 4.8 days$_{t>10°C}$ decade$^{-1}$;
2. deepening of the AL at a rate of 15–20 cm decade$^{-1}$ (CALM) accompanied by mobilization of previously frozen organic carbon;
3. formation of thermokarst lakes and sub-lake taliks as a result of permafrost-thaw induced ground subsidence and surface inundation;
4. subsurface drainage of lakes through their taliks (according to Landsat-7 satellite data, the regional lake area decreased by 10.4% over 2000–2015 period) followed by waterlogging of drained lake basins.

To reveal how these changes affect $CH_4$ emissions from low-Arctic tundra wetlands of WSL, we carried out $CH_4$ flux measurements in different permafrost ecosystems of Pur-Taz interfluve in the summer seasons of 2023–2025. According to our results, measured $CH_4$ fluxes from dry polygonal tundra did not exceed 0.35 mg$CH_4$ m$^2$·h$^{-1}$ (median −0.01). Upon waterlogging, much higher flux values (up to 11.0 mg$CH_4$ m$^2$·h$^{-1}$) were observed (median 1.7). Thermokarst lakes emitted $CH_4$ at a rate of 0.1−9.0 mg$CH_4$ m$^2$·h$^{-1}$ (median 0.4), whereas $CH_4$ fluxes from their young and old drained basins were up to 21.6 (median 5.6) and 9.0 mg$CH_4$ m$^2$·h$^{-1}$ (median 4.6), respectively.

Among the above-mentioned ecosystem changes, lengthening of the growing season, deepening of the AL as well as waterlogging are the key ones that enhance $CH_4$ emissions from permafrost ecosystems of WSL low-Arctic tundra.

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# How temperature controls methane fluxes and methanogenic pathways at polygonal tundra of Samoylov Island in the Lena River Delta (Northern Siberia)

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## ABSTRACT

Wetlands are the largest natural source of methane ($CH_4$) – the second most potent greenhouse gas (GHG) in terms of contribution to global warming. Among them, Arctic permafrost-affected wetlands are extremely vulnerable to GHG-induced warming. As permafrost degrades, organic carbon becomes entrained in the active layer (AL) and converted to $CH_4$ by methanogens using mainly acetate or carbon dioxide as substrate (acetoclastic and hydrogenotrophic pathway, respectively). As a result, $CH_4$ emissions from Arctic wetlands increase in a positive feedback manner.

In the summer seasons of 2023 and 2024, we studied temperature controls on $CH_4$ fluxes and its production at polygonal tundra wetland of Samoylov Island in the Lena River Delta. The study area represents a mosaic of ice-wedge polygons with wet low centers and elevated drained rims. The increasing trend of summer $CH_4$ emissions from Samoylov polygonal tundra (Rößger et al., 2022) is determined by: a) water regime changes due to the degradation of intact low-center polygons (LCP); b) deepening and warming of AL. LCP degradation affect $CH_4$ emissions depending on local relief features whereas AL depths and temperatures are expected to increase further.

We monitored $CH_4$ fluxes at the wet (5 LCP) and drained (two intact rims and a high-center polygon with degraded rim) microsites at the peak of growing season by static chamber method. Measured fluxes from wet LCP (0.8–4.5 $mgCH_4 \cdot m^{-2} \cdot h^{-1}$) were by two orders of magnitude higher than those from drained microsites and were poorly correlated with air and soil temperatures (Fig. 1), while their correlations with dissolved $CH_4$ concentrations in pore water were significant ($r_s$ = 0.64 and 0.55 at the depth of 10 and 15 cm, respectively). This was indicative that anaerobic $CH_4$ production and its release from AL occur on different timescales.

To study temperature sensitivity of $CH_4$ production, peat was sampled below the water table and incubated anaerobically. Based on $CH_4$ accumulation rates (Fig. 2), $Q_{10}$ coefficient between 5 ºC (mean value at the sampling depth) and 10 ºC was estimated to be 22. Parallel incubations with inhibitors of methanogenesis revealed that such a high value was due to an overwhelming contribution of acetoclastic pathway to overall $CH_4$ production. As its contribution was found to rise from 65% at 5 ºC to ~90% at 10 ºC, expected increase in AL temperatures may enhance $CH_4$ emissions from Arctic polygonal wetlands by an order of magnitude over centennial timescale.

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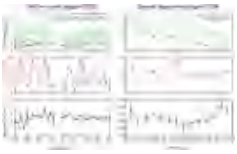


Fig.1. Dynamics of $CH_4$ fluxes and air/soil temperatures at some studied polygonal tundra microsites

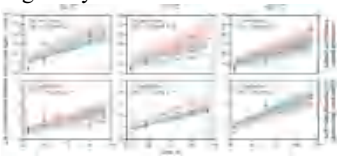


Fig.2. $CH_4$ accumulation-and calculated $CH_4$ production in incubation experiments

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# Contrasting effects of inorganic vs. organic nitrogen deposition on soil respiration: Evidence from a 10-year field experiment

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## ABSTRACT

Understanding effects of future climate change requires accurate estimates of the impacts of atmospheric nitrogen (N) deposition on ecosystem carbon (C) cycling. Most previous studies have focused on inorganic rather than organic N deposition in influencing C fluxes. However, organic N is a substantial component of N deposition. Here we report the response of grassland soil respiration to 10 years of experimental addition of organic N (ON) and inorganic N (IN) separately and in mixture. Soil respiration increased greatly with N addition, regardless of N form, in the first five years. However, after six years of experimental additions, these effects of IN were reversed, and by 10 years, respiration from IN plots decreased by 24% and 69% relative to control and ON treatments, respectively. The divergent temporal responses of soil respiration to different N forms resulted from differences in the relative contributions of autotrophic respiration (RA) and heterotrophic respiration (RH), which mediated by the cumulative effects of N-induced soil acidification (pH decrease). The sharp decline of RH in response to IN addition corresponded to greater acidification in the IN treatment. Collectively, our findings indicate that the response of soil respiration to decade-long N deposition was modulated by soil pH and highlight that organic N in atmospheric deposition should be considered to improve understanding of how grassland ecosystems respond to long-term N deposition.

**Key-words:** inorganic N deposition, organic N deposition, grassland soil respiration, soil acidification.

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# Mechanisms and Mitigation Potential for Carbon Sequestration and Greenhouse Gas Emissions in Paddy Soils under Climate Change

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**ABSTRACT**

This study focuses on the response mechanisms of soil organic carbon (SOC) sequestration and greenhouse gas emissions in paddy fields under climate change, aiming to elucidate the effects of elevated $CO_2$ concentration ($eCO_2$) and warming on carbon cycling processes in paddy ecosystems, and to evaluate the potential of biochar as a measure for carbon sequestration and emission reduction. Through in situ Warming-Free Air $CO_2$ Enrichment (T-FACE) platforms, long-term open-top chamber (OTC) experiments, and data analysis of global biochar trials, the impacts of $eCO_2$, warming, and their interactions on SOC dynamics, $CH_4$ and $N_2O$ emissions, as well as the underlying microbial and biogeochemical driving mechanisms, were systematically investigated. The results indicate that $eCO_2$ significantly increased subsoil SOC content by enhancing plant- and microbe-derived carbon inputs without stimulating the decomposition of native soil carbon. Elevated $CO_2$ also raised soil dissolved organic carbon (DOC) and acetate levels, thereby enhancing methanogenic potential and significantly increasing $CH_4$ emissions, whereas warming and its interaction with $eCO_2$ had no significant effect on $CH_4$ emissions. The interaction between $eCO_2$ and warming exhibited nonlinear characteristics in SOC and $CH_4$ responses, the mechanisms of which require further clarification. Biochar demonstrated sustained effects on carbon sequestration, emission reduction, and yield improvement. Long-term biochar application significantly reduced $CH_4$ and $N_2O$ emissions, enhanced SOC sequestration, and increased crop yield by approximately 10.8%, with almost no negative impacts on soil health. This study clarifies the mechanism by which $eCO_2$ influences SOC accumulation in paddy soils through regulating carbon input and decomposition processes, and reveals that biochar retains significant potential for carbon sequestration and emission reduction under climate change. Future research should further quantify the types of interactions among climatic factors to support adaptive management strategies for paddy systems in response to climate change.

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# Global Distribution Patterns of Phytolith-Occluded Carbon in Terrestrial Ecosystems Based on Meta-Analysis and Machine Learning

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## ABSTRACT

Since the onset of industrialization, atmospheric carbon dioxide ($CO_2$) concentrations have increased rapidly and have reached their highest levels in at least two million years. The IPCC has clearly stated that the accumulation of atmospheric $CO_2$ driven by human activities has significantly altered the Earth's energy balance by enhancing the greenhouse effect, constituting the dominant driver of current global warming, and exerting profound impacts on global and regional climate systems through perturbations of terrestrial carbon cycling, hydrological processes, and ecosystem feedback mechanisms.

Terrestrial ecosystems are a critical component of the global carbon cycle, characterized by pronounced diversity and hierarchical organization among carbon pools, including both active carbon pools such as vegetation biomass carbon and soil organic carbon (SOC), as well as more stable pools such as inorganic carbon. For decades, research has primarily focused on net primary productivity and the formation and turnover of SOC; however, these carbon pools are relatively dynamic across temporal scales and highly sensitive to climatic fluctuations and land-use change. In contrast, carbon pools with longer residence times and higher stability play an irreplaceable role in regulating atmospheric $CO_2$ concentrations under global change scenarios, and their identification and quantitative assessment are essential for accurately estimating the long-term carbon sink potential of terrestrial ecosystems. Nevertheless, such stable carbon pools remain substantially underestimated within existing carbon cycle frameworks, and their formation mechanisms, sources of stability, and spatial distribution patterns have yet to be systematically elucidated.

Phytoliths are amorphous silica ($SiO_2$) particles formed in plants through the uptake of soluble silicon from soils—primarily in the form of monosilicic acid—via the root system, followed by precipitation within cell walls, cell lumens, or intercellular spaces. During phytolith formation, a fraction of photosynthetically fixed organic carbon becomes encapsulated and occluded within the silica matrix, forming phytolith-occluded carbon (PhytOC). The organic carbon occluded within phytoliths can be preserved for extended periods in soil environments, thereby constituting a long-term stable carbon pool with considerable potential in terrestrial ecosystems. This long-term stability primarily arises from the intrinsic dissolution kinetics of phytoliths and multiple protective mechanisms operating within soil environments.

From a micro-process perspective, phytolith dissolution behavior is jointly regulated by morphological characteristics, chemical composition, and environmental conditions. Studies have shown that phytolith dissolution rates are significantly negatively correlated with ambient initial silicon concentrations (Nakamura et al., 2020), and that their spatial distribution within plant tissues exerts a strong influence on stability: compared with structurally fragmented phytoliths with larger specific surface areas (phytolith fragments), phytoliths deposited within cell lumens and cell walls generally exhibit greater structural integrity and lower dissolution rates (Nakamura et al., 2020). In soil environments, phytoliths can further be differentiated into fast-cycling and stable pools, reflecting the coexistence of young, rapidly recycled biogenic silica reservoirs and old, slowly dissolving stable reservoirs; the latter are typically dominated by dense morphotypes such as spherical phytoliths and exhibit markedly reduced dissolution rates. Although phytoliths, as amorphous silica minerals, are overall more soluble than crystalline silicate minerals, their dissolution is strongly constrained by soil pH, hydration state, and adsorption of metal elements, particularly through complexation with aluminum on phytolith surfaces, which effectively suppresses silica framework dissolution and prolongs phytolith residence time in soils (Cornelis et al., 2016).

Meanwhile, phytoliths in soils can acquire additional physical protection by associating with organic matter and clay minerals to form micro-aggregate structures. The formation of micro-aggregates substantially reduces direct contact between phytoliths and soil solutions, thereby further slowing dissolution processes. Higher contents of organic matter and clay in forest soils favor the stabilization of micro-aggregates, resulting in greater phytolith preservation compared with grassland or sparsely vegetated soils. In addition, under acidic conditions, phytolith surfaces readily develop coatings of hydroxyaluminosilicate precipitates, which not only inhibit silica dissolution but also significantly enhance the physical and chemical stability of phytoliths in soils.

Compared with SOC, PhytOC exhibits substantially higher stability due to encapsulation within a siliceous shell that provides enhanced structural protection, allowing residence times in soils to extend to several millennia (Liu et al., 2025). In contrast, SOC is prone to rapid losses following land-use changes such as grassland cultivation, with declines reaching up to 50% (Song et al., 2024). Fertilization experiments further demonstrate that PhytOC predominantly exists in stable forms within phytoliths and is resistant to microbial decomposition (Rutkowska et al., 2024). Principal component analyses indicate that PhytOC content is significantly correlated with soil pH and mineral elements such as Al and Fe, which enhance stability by suppressing phytolith dissolution (Wang et al., 2023). Even in karst bamboo forest soils characterized by low bulk density and unfavorable conditions for carbon preservation, PhytOC stability remains markedly higher than that of bulk SOC (Song et al., 2024). In oat and barley cropping systems, although PhytOC contents are significantly lower than SOC, their longer residence times still confer a pronounced stability advantage (Rutkowska et al., 2024).

The stability of PhytOC has not only been validated mechanistically but its sequestration potential has also been quantified using multiple metrics. At the global scale, the annual sequestration potential of PhytOC in bamboo forests has been estimated at $2.05 \pm 0.17$ Tg $CO_2$, accounting for approximately 11% of the contemporaneous annual atmospheric $CO_2$ increase (Liu et al., 2025). Field fertilization experiments show that PhytOC accumulation in oat fields ranges from 14.94 to 41.73 kg e- $CO_2 \cdot ha^{-1}$, with silicon fertilization increasing PhytOC contents by approximately 2.5-fold (Rutkowska et al., 2024). Statistical analyses further indicate that PhytOC stocks in moso bamboo and Neosinocalamus affinis forests range from 0.49 to 2.07 $t \cdot hm^{-2}$, and that mature stands store 1.5–2 times more PhytOC than young stands, reflecting a pronounced age-related accumulation effect (Wang et al., 2023). In karst soils, PhytOC can even account for up to 82% of SOC, highlighting its exceptionally high long-term sequestration potential (Liu et al., 2025).

Because phytolith formation and dissolution stability are jointly regulated by multiple factors, phytolith contents and their associated carbon vary substantially among plant taxa, plant organs, and ecological environments. Gramineous species possess highly efficient silicon uptake, transport, and accumulation mechanisms, enabling large quantities of soluble soil silicon to be translocated to aboveground tissues, thereby significantly promoting phytolith formation and enhancing carbon sequestration potential (de Tombeur et al., 2024). At the organ scale, phytolith carbon exhibits pronounced organ-level heterogeneity, with leaves, stems, straw, and roots contributing differently to total phytolith carbon stocks across plant types (Zhang et al., 2019) (Parr et al., 2010).

In addition to vegetation traits, environmental conditions also play a critical role. Soil-available silicon is widely regarded as a key material constraint on phytolith formation, with its supply directly controlling phytolith content and accumulation rates (Wang et al., 2022). The amount of silicon absorbed by plants determines the material basis for phytolith formation and thus directly influences phytolith production (Nakamura et al., 2020). In highly weathered soils, this phytolith-driven biological silicon cycle can even dominate silicon fluxes, as plants convert soil LSi and PSi into PhSi, enhancing silicon bioavailability within the soil–plant system and continuously influencing the coupled cycling of silicon and carbon (Cornelis et al., 2016).

Meanwhile, climatic factors such as temperature and precipitation indirectly affect phytolith formation intensity by regulating plant productivity, growth cycles, and silicon uptake, whereas soil physicochemical properties—including pH, organic matter content, and nutrient status—further control phytolith accumulation and preservation by influencing silicon dissolution, transport, and phytolith stability in soils (de Tombeur et al., 2024). (Deng et al., 2025)Deng employed a meta-analytical approach to comprehensively evaluate the effects of environmental factors on soil phytolith contents within a unified statistical framework. The results indicate that climatic conditions, soil physicochemical properties, and vegetation types all exert significant influences on soil phytolith contents; however, the direction and magnitude of these effects exhibit high heterogeneity among studies and ecosystems, reflecting the strong multi-factor control over phytolith formation and accumulation processes.

However, as soil phytoliths originate from plant-internal formation, are subsequently transferred via litter inputs, and gradually accumulate in soils, their contents are not only controlled by soil environmental conditions but are also highly dependent on plant silicon uptake capacity, organ allocation patterns, and litter deposition and decomposition processes. Existing meta-analyses that focus solely on soils provide valuable insights into environmental controls at the soil scale, but they are unable to disentangle the relative contributions of different factors during plant formation, litter transformation, and soil preservation stages, nor can they fully elucidate the integrated contributions of these processes to final soil phytolith contents.

Despite substantial advances in understanding phytoliths and their carbon sequestration functions, notable knowledge gaps remain. Most existing studies are based on local-scale observations, with limited geographic coverage and ecosystem representation; data are fragmented and indicators are inconsistent across studies, constraining large-scale synthesis. Moreover, many studies emphasize the independent effects of single or a few environmental factors, while systematic assessments of multi-factor interactions among vegetation, soil, and climate remain scarce. Methodologically, conventional statistical models have limited capacity to capture complex nonlinear relationships, thereby restricting accurate prediction of phytolith spatial patterns and their driving mechanisms.

Against this background, this study uses measured phytolith data from terrestrial ecosystems to systematically analyze the formation mechanisms and spatial distribution patterns of phytoliths and their associated carbon. Specifically, it aims to elucidate how climatic factors, soil properties, and vegetation types jointly regulate the spatial differentiation of phytolith and phytolith carbon contents, and to develop predictive models based on published empirical datasets to enable quantitative estimation of phytolith contents at broader spatial scales. By integrating global phytolith measurements with multi-factor statistical analyses, meta-analysis, and machine-learning approaches, this study seeks to overcome current limitations in spatial scale, analytical methods, and predictive capacity, and to develop predictive models based on published empirical datasets, enabling quantitative estimation of phytolith contents at broader spatial scales.

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# Divergent but coupled responses of soil organic and inorganic carbon to global warming and aridity

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## ABSTRACT

Soil organic carbon (SOC) and inorganic carbon (SIC) jointly determine terrestrial carbon (C) storage and its climate feedbacks, yet their coupled responses to warming and drought remain poorly quantified. We synthesize two global analyses to resolve how climate warming and aridity regulate SOC–SIC dynamics across ecosystems and soil depths. First, using a global soil-profile dataset (25,492 observations) and integrating historical baseline comparisons, synthetic control analysis, and meta-analysis, we quantified warming effects in cropland, grassland, and forestland. Relative to the pre-industrial period, mean annual temperature has increased by 1.90 ± 0.67 °C, corresponding to a net loss of 126.8 Pg C in soil total carbon (STC). Responses varied significantly across C pools, ecosystem types, soil depths, and warming levels. Initial soil C content emerged as the strongest predictor of the direction and magnitude of warming-induced change, while cropland the most variable response. Second, focusing on cropland, we assessed drought effects using global soil-profile C data (11,585 observations). Average STC stocks in the 0–30 cm, 30–100 cm, and 100–200 cm layers were 8.0, 16.7, and 21.6 kg C $m^{-2}$, respectively. STC in deep soils (100–200 cm) declined linearly along the drought gradient, whereas surface STC exhibited a nonlinear response, reflecting distinct moisture sensitivities of SOC and SIC. Notably, the ratio of SIC to STC increased with increasing aridity, indicating a proportionally larger contribution of SIC under drier conditions. Irrigation, a major drought adaptation strategy, increased SIC contributions in dry sub-humid regions but tended to reduce it elsewhere. Together, our integrated results demonstrate that SOC and SIC respond divergently yet interactively to climate drivers. Accurate soil C budgets and climate mitigation assessments therefore require explicit inclusion of SIC alongside SOC, particularly in dryland and agricultural systems facing progressive warming and intensifying drought.

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# $CO_2$ emission following total vegetation removal: a pilot study

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**ABSTRACT**

Icelandic heathlands, currently categorized as grasslands under the LULUCF framework, are widespread ecosystems with complex carbon dynamics that are still not fully captured by existing accounting methods. Current estimates in the national greenhouse gas inventory rely on IPCC default Tier 1 emission factors and therefore involve considerable uncertainty. Ongoing research aims to improve the understanding of carbon processes in heathland systems and to advance greenhouse gas accounting for grasslands to higher methodological tiers. In this context, land-use options are evaluated as part of broader climate mitigation and land management strategies. Forestry is one such land-use option that is often considered for its potential contribution to carbon sequestration. Current approaches in afforestation include using TTS Hydraulic Power Disc Trenchers to tear up the vegetation and remove the topsoil before planting. This causes considerable disturbances and increases the probability of carbon losses which are not accounted for when the total carbon budget is calculated. Here we test the hypothesis that disturbances following such approaches will cause increased $CO_2$ emissions. Twelve 1 $m^2$ plots were selected in fall of 2024 and baseline $CO_2$ emission established with regular measurements until July 2025 when the vegetation was totally removed from six randomly selected treatment plots. The measurements have since been continued in all plots to explore the long-term effect of the treatments. The experiment is located in a low-production artificial heathland site (managed experimental area) and was chosen for accessibility. Preliminary results show that there was no active carbon sequestration before vegetation removal. However, we found a significant increase in $CO_2$ emissions after the vegetation was removed, while the $CO_2$ flux in the control plots remained stable. This suggests that the management approach used here will increase $CO_2$ emissions compared to intact land, even though this pilot study was not conducted under optimal conditions. We plan to repeat this experiment under more realistic conditions in the future to get more representative results that can be related to current afforestation management practices.

# Greenhouse Gas Fluxes and Their Environmental Drivers in a Coastal Peatland of the Kamchatka Peninsula

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## ABSTRACT

This study presents the first comprehensive measurement of greenhouse gas emissions from a coastal peatland in Kamchatka, a region with a significant gap in terms of field data on methane and carbon dioxide fluxes. Research was conducted in September 2025, on a peatland 19 km east of Petropavlovsk-Kamchatsky. High-frequency monitoring (every two hours) was conducted over three full days at two adjacent sites (Ecosystem I and II) within the peatland. The water table was at or above the soil surface at both sites, with marginally higher levels recorded in Ecosystem II. Methane fluxes and ecosystem respiration were measured using the static dark chamber method with a portable LI-COR 7810 gas analyzer, alongside key environmental parameters.

Median $CH_4$ fluxes were similar: 1.11 and 1.31 $mgCH_4 \cdot m^{-2} \cdot h^{-1}$ for Ecosystems I and II, respectively, and median $CO_2$ fluxes were 317.9 and 356.6 $mgCO_2 \cdot m^{-2} \cdot h^{-1}$. The key difference was the flux dynamics: Ecosystem I showed stable emissions with a gradual decline, while Ecosystem II was characterized by sharp peak events of both gases (up to 7.52 $mgCH_4 \cdot m^{-2} \cdot h^{-1}$ and 644.5 $mgCO_2 \cdot m^{-2} \cdot h^{-1}$), several of which were synchronous in time.

Spearman correlation analysis identified the main environmental drivers of flux variability. In Ecosystem I, fluxes of both gases positively correlated with soil surface temperature ($r_s$=0.47 for $CH_4$, and 0.60 for $CO_2$) and negatively with wind speed ($r_s$=-0.48 and -0.54, respectively). In Ecosystem II, the key factor for $CH_4$ was air temperature ($r_s$=0.51) and atmospheric pressure ($r_s$=-0.48), indicating a possible contribution of ebullition.

Analysis of diurnal dynamics showed that restricting measurements to daytime (11:00–16:00) leads to a systematic overestimation. For Ecosystem II, the average daytime $CH_4$ flux (3.54 $mgCH_4 \cdot m^{-2} \cdot h^{-1}$) was 74% higher than the 24-hour average (2.04 $mgCH_4 \cdot m^{-2} \cdot h^{-1}$). For Ecosystem I, the overestimation was 10% (1.30 vs. 1.18 $mgCH_4 \cdot m^{-2} \cdot h^{-1}$).

This work fills a data gap and highlights the importance of accounting for diurnal cycles and spatial heterogeneity for accurate emission assessment for Kamchatka peatlands.

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# Decoupling the "Pump" and the "Tomb": Depth-Dependent Soil Organic Carbon Stabilization Mechanisms under Long-Term Conservation Tillage

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**ABSTRACT**

Conservation tillage (CT), particularly no-till with straw mulching, is a critical strategy for enhancing soil organic carbon (SOC) sequestration. However, current understanding is largely confined to the surface layer, leaving the depth-dependent stabilization mechanisms—specifically the interplay between plant-derived carbon (PC), microbial-derived carbon (MC), and mineral associations—poorly resolved.

To address this gap, we synthesized data from two long-term field experiments (8 and 14 years) located in distinct temperate agroecosystems in Northeast and North China. We integrated molecular biomarkers (amino sugars and lignin phenols), enzyme stoichiometry, and physical fractionation (POC vs. MAOC) with structural equation modeling to deconstruct the vertical stratification of SOC stabilization.

Our results reveal that CT does not merely increase SOC inventory but fundamentally re-engineers the soil profile into two functional niches with divergent stabilization pathways:

The Topsoil Synergistic Niche (0–20 cm): Functioning as the "Microbial Carbon Pump," this layer is resource-rich. CT significantly enhanced C- and N-acquiring enzyme activities, accelerating the turnover of plant residues. Here, SOC accumulation is driven by a synergistic pathway: fresh residues primarily form Particulate Organic Carbon (POC), while simultaneous high microbial activity transforms labile inputs into microbial necromass, which then stabilizes as Mineral-Associated Organic Carbon (MAOC).

The Subsoil Preservation Niche (20–30 cm): Functioning as a "Carbon Tomb," this layer is resource-limited. We found a decoupling of stabilization pathways. The persistence of microbial necromass (the dominant component of subsoil SOC) became independent of contemporary microbial activity, relying instead on direct physicochemical protection (mineral entombment). Paradoxically, the stabilization of recalcitrant plant lignin at this depth required a "microbial gatekeeper" step—transformation by specialized communities was a prerequisite for subsequent mineral association.

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# A Mechanistic–AI and Remote-Sensing Assimilation Framework to Quantify Straw-Return Impacts on Soil Carbon Fluxes and Soil Health

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**ABSTRACT**

Reliable quantification of soil carbon fluxes is fundamental for climate mitigation and soil health, yet major uncertainties persist when scaling management effects from field experiments to regions. Straw return is widely promoted to increase soil organic carbon (SOC) and improve fertility, but its net climate benefit depends on coupled responses of SOC turnover and greenhouse-gas fluxes ($CO_2$, $CH_4$, $N_2O$) under diverse soils, climates, and management regimes.

We present a conference-ready framework that integrates process-based modeling, knowledge-guided machine learning, and satellite remote sensing to assess and optimize straw-return strategies across major cereal systems. A calibrated process model is used to represent soil C–N cycling and carbon–GHG flux pathways under varying residue inputs and agronomic practices. Machine-learning modules are then applied for residual correction and ensemble fusion to reduce structural bias and improve transferability while maintaining mechanistic consistency. Sentinel-2 time series are used to retrieve residue cover and crop status, and are assimilated to constrain key model states/parameters and enable consistent plot-to-regional upscaling. Finally, multi-objective optimization (e.g., NSGA-II) is employed to identify region-specific straw management solutions that jointly target SOC accrual, net $CO_2$-equivalent mitigation, and yield stability.

The framework is designed to deliver spatially explicit estimates of soil carbon fluxes and management-sensitive uncertainty bounds, providing actionable evidence for carbon farming and climate-smart soil management.

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# Evaluating global soil carbon sequestration and loss: an expert assessment of their role in climate mitigation and adaptation

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## ABSTRACT

Soils represent the largest terrestrial reservoir of carbon, and their good management has been widely discussed as a means of partially compensating for global greenhouse gas emissions from anthropogenic sources and as a means to make soils more resilient to climate change. Yet, substantial uncertainties remain regarding the realistic, durable, and scalable contribution of soil organic carbon (SOC) sequestration to climate change mitigation and adaptation. In this assessment, we provide a global expert assessment of the potential role of SOC sequestration and avoided SOC loss in contributing to climate targets. We conduct an international survey designed to gather expert judgements on three key dimensions: (a) the magnitude of $CO_2$-equivalent emission reductions achievable through SOC sequestration by 2050 under realistic, sustainable land-management practices; (b) SOC losses resulting from the conversion of natural or semi-natural ecosystems to cropland, and the proportion of these losses that could feasibly be recovered by 2050 through improved cropland management; and (c) the plausible time horizon over which SOC sequestration can deliver measurable and lasting climate-mitigation and adaptation benefits.

To strengthen the scientific and policy relevance of this assessment, we explicitly distinguish between the mitigation potential of SOC sequestration (new carbon inputs) and SOC protection (avoided losses), as these mechanisms differ in magnitude, reversibility, and timescales. This expert-based approach complements empirical measurements and modelling studies, helping clarify persistent uncertainties across ecosystems and management contexts. It also contributes to ongoing discussions on the realistic contribution of soils to achieving the Paris Agreement targets for 2050.

Here, we present the preliminary results, motivation, and objectives of this ongoing assessment. We also extend an open invitation to soil scientists, biogeochemists, agronomists, modellers, and related experts worldwide to participate in and strengthen the evidence base needed to evaluate the global mitigation and adaptation potential of SOC.

**Keywords:** Carbon stock; Expert elicitation; 4 per 1000

# Integrating Soil Properties and Management into Data-Driven Modeling of Soil $CO_2$Efflux in Urban Green Roofs

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**ABSTRACT**

Soil $CO_2$ efflux (respiration), driven by microbial activity, root respiration, and physical diffusion processes, is a key component of the carbon balance in urban greening systems. Although green roofs are recognized for their potential to sequester atmospheric carbon and mitigate urban heat, accurate evaluation of their carbon reduction performance requires comprehensive consideration of $CO_2$ emissions from soil under varying environmental, soil, and management conditions.

In this study, soil $CO_2$ efflux was monitored at four urban green roof sites in Seoul and Goyang, South Korea, from March to October 2025, encompassing extensive, semi-intensive, and intensive systems with diverse vegetation types, soil depths, and substrate compositions. Soil $CO_2$ efflux was measured using a portable gas analyzer (EGM-5), accompanied by concurrent observations of air temperature and humidity, soil temperature, and soil moisture to capture atmospheric and belowground microclimatic controls. In addition, soil physicochemical properties, including soil pH, bulk density, total porosity, and soil carbon stocks, as well as site-specific management variables such as irrigation frequency and maintenance intensity, were incorporated into the analysis.

We applied a data-driven modeling framework that accounts for nonlinear interactions, temporal variability, and site heterogeneity among multiple environmental drivers. Principal component analysis (PCA) and cluster classification revealed distinct groupings of sites based on combined atmospheric conditions, soil microclimate, soil properties, carbon stocks, and management regimes. Furthermore, cluster-specific mixed-effects models demonstrated that the sensitivity of soil $CO_2$ efflux to air and soil temperature, moisture, and soil physicochemical properties varies substantially across green roof types and management intensities.

These results indicate that integrating atmospheric variables, soil microclimatic conditions, soil physicochemical characteristics, and management-related factors significantly improves the interpretability and predictive performance of soil $CO_2$ efflux models. This study underscores the importance of holistic, data-driven approaches for accurately characterizing soil respiration dynamics and carbon balance in urban green roof systems.

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# Monitoring Soil Carbon Storage and Soil Respiration in Street-Level Green Infrastructure

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**ABSTRACT**

Urban green infrastructure is widely recognized as a multifunctional system that provides climate regulation, ecosystem services, and social benefits. However, existing studies on carbon fluxes in urban green spaces have primarily focused on natural soils such as forests and parks, while measurement-based investigations of carbon fluxes in artificial green infrastructure, including green roofs and street-level greenery, remain limited.

The objective of this study is to quantitatively assess soil carbon storage and soil respiration in street-level green infrastructure through field-based monitoring and to characterize carbon dynamics during the operational phase. Study sites were selected to represent typical street-level green infrastructure types—flowerbeds and planters—which differ in soil depth, substrate composition, planting structure, and management practices.

Soil carbon storage was estimated by analyzing total carbon content in soil samples and measuring bulk density to calculate areal carbon stocks. In addition, thermogravimetric analysis (TGA) was conducted to examine the compositional characteristics of soil carbon. Soil respiration was measured in situ using a portable closed-chamber $CO_2$ measurement system (EGM-5). Monitoring was conducted across multiple periods to capture seasonal variations associated with changes in air temperature and soil moisture conditions.

The results showed substantial variability in soil carbon storage across street-level green infrastructure systems, depending on system type, soil properties, and vegetation characteristics. Soil respiration rates increased significantly with rising seasonal temperatures and higher soil organic matter content, and during certain periods, soil $CO_2$ efflux exceeded plant carbon uptake.

This study provides empirical, measurement-based evidence of both soil carbon storage and emissions in artificial ground-based green infrastructure, thereby extending the scope of urban soil carbon research that has traditionally focused on natural soils. The findings suggest that the effective use of artificial green infrastructure as a climate change mitigation strategy requires integrated consideration of soil composition and operational carbon dynamics during both the design and maintenance stages. The results also provide a foundational dataset for the development of urban-scale carbon accounting frameworks.

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# Soil Carbon Fluxes in Agroecosystems with Annual and Perennial Grasses in the Moscow region of Russia

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## ABSTRACT

Climate change, caused by increasing greenhouse gases (GHG) concentrations in the atmosphere, is one of the most serious threats to the sustainability of the Earth's ecosystems and food security. Soils play a key role in the global carbon cycle, acting as both sources and sinks of GHGs. One way to prevent further climate change is to increase the carbon sequestration in agricultural soils. We can use carbon-saving farming technologies for this purpose, particularly the seeding of perennial grasses and green manure. The positive effects of grass seeding on soil carbon accumulation and soil health are widely known, but the high variability of carbon dioxide ($CO_2$) and methane ($CH_4$) fluxes requires representative data for soils in different regions. Obtaining such data for one region of Russia was the aim of this study.

We investigated agroecosystems of Chashnikovo carbon testing site, which is located in about 40 km northwest of Moscow, in June–August 2024 and 2025. The climate is moderate continental; soils are Albic Retisols (Aric, Loamic, Cutanic). Five monitoring plots (25–30 $m^2$) were located in three adjacent fields. Two plots were with annual green manure grasses (white mustard and vetch-oat mixture) and another two plots were with perennial grasses (legume-cereal grasses and hybrid giant miscanthus). One plot was fallow, without plants. GHG fluxes measured using a portable chamber and a Li-7810 gas analyzer (Li-Cor, the USA) after the preliminary removal of the aboveground part of the plants. The soil temperature and moisture, soil density, particle size distribution, pH, aboveground and underground phytomass, and carbon content in soils and plants were measured, and the potential microbial production of $CO_2$ by soils was calculated based on the their basal respiration.

The investigated soils acted as a weak sink for atmospheric $CH_4$ and emitted $CO_2$ in amount less than or comparable to that which could be assimilated in the phytomass of green manure and perennial grasses.

The rate of $CH_4$ consumption by soils depended on the crop grown and varied from 0,05 to 0,75 $mgC \cdot m^{-2} \cdot day^{-1}$. In soils under fallow, mustard, and perennial grasses, it was highest in July, while under the vetch-oat mixture and miscanthus, it gradually increased throughout the summer. Total summer $CH_4$ uptake by soils was highest under miscanthus, decreased statistically significantly under the vetch-oat mixture, perennial grasses and mustard.

Soil $CO_2$ emission was determined by changes in soil moisture and plant growth stages and varied from 2 to 12 $gC \cdot m^{-2} \cdot day^{-1}$. Total summer fluxes were highest in soils under perennial grasses, decreased under miscanthus, vetch-oat mixture and mustard. Increased $CO_2$ emission from soils under perennial crops was due to higher microbial $CO_2$ production and active root respiration, resulting in the formation of statistically significantly greater belowground phytomass than under green manure.

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# Drivers and Spatial Variability of $CO_2$ Efflux in Agrosilvopastoral System and Native Vegetation in the Brazilian Cerrado

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**ABSTRACT**

Integrated agricultural systems (IAS) are nature-based solution that can support the recovery of degraded areas. Given the central role of soil as both a carbon source and reservoir, the inclusion of trees in pasture systems can significantly influence nutrient cycling and carbon dynamics. Soil $CO_2$ efflux, a key component of the carbon cycle, is strongly affected by biotic and abiotic factors, including temperature, soil moisture, root biomass, and land management practices. In IAS, microclimate alterations and increased organic inputs near tree rows can modulate $CO_2$ emissions and impact soil carbon dynamics. This study evaluated the effects of eucalyptus trees in an agrosilvopastoral system on $CO_2$ efflux, comparing it with nominal pasture and native vegetation. This study evaluated the effects of *Eucalyptus* trees in an agrosilvopastoral system on soil $CO_2$ efflux, comparing it with nominal pasture and native vegetation. Soil $CO_2$ efflux exhibited pronounced seasonal patterns across all systems, with higher emissions during the rainy season, highlighting the dominant role of soil moisture in regulating soil respiration. In the agrosilvopastoral system, elevated $CO_2$ efflux near tree rows was associated with greater shading, litter accumulation, and root biomass, which together created a more stable microclimate conducive to microbial activity. In contrast, areas farther from the trees and the nominal pasture exhibited lower moisture retention and higher thermal variability, resulting in reduced $CO_2$ emissions. In native vegetation, dense ground cover and extensive root systems maintained stable microclimatic conditions, supporting higher $CO_2$ efflux compared to nominal pasture despite lower light availability. These results confirm that soil respiration is strongly governed by the interaction of moisture, temperature, root activity, and surface residue, and emphasize the critical role of vegetation structure in modulating soil carbon fluxes in both managed and natural systems.

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# The permanence of carbon sequestration in agricultural soil – what do we (not) know

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## ABSTRACT

Carbon sequestration in agricultural soils is a promising strategy for mitigating carbon dioxide ($CO_2$) emissions while simultaneously enhancing soil health. However, the permanence of sequestered carbon, defined as the duration over which carbon remains stored without re-emission to the atmosphere, in agricultural soil can be affected by soil management and land use changes. This makes the climate mitigation potential of agricultural soils uncertain. The stability of soil organic carbon depends on a complex interplay of intrinsic soil characteristics and (historical) land use and soil management. There are still quite some knowledge gaps on this interplay. In particular, it is still unknown which factors influence the permanence and to what extent. To obtain more insight, data on the $CO_2$ release rate after stopping the application of a carbon mitigation measure is essential. Long-term experiments (LTEs) (>30 years) provide valuable insight in the effect of carbon mitigation measures on soil organic carbon content, but only a few LTE studies also analysed the $CO_2$ release after stopping. These few LTE studies showed that sequestered carbon is released again, but the new equilibrium is in all LTEs higher compared to the baseline (i.e., fields without carbon sequestration measures). This suggests that carbon mitigation measures are always beneficial for $CO_2$ mitigation. We also learned from this analysis that soil management and historical land use seem to play an important role in permanence of carbon sequestration, and therefore the analysis was extended by a space-for-time analysis on data of the Dutch soil sampling campaign. These data were combined with soil management information and historical land use maps that go back until 1900. This analysis confirmed that land use change (cropland to grassland and grassland to cropland) plays a significant role in the carbon sequestration and release rate. It is recommended that both, the duration of applying a carbon mitigation measure and historical land use, are taken into account when assessing the long-term contribution of agricultural soils to climate change mitigation.

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# Soil Organic Carbon: A Key Player for Fertility, Climate, and Healthy Land

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**ABSTRACT**

Soil organic carbon (SOC) constitutes a fundamental component of terrestrial ecosystems, playing an indispensable and multifaceted role in maintaining ecological functions, productivity, and global biogeochemical balances. This review synthesizes current knowledge to elucidate the multifaceted mechanisms through which SOC underpins ecosystem functionality and sustainability. The review first establishes the foundational role of SOC in soil health, detailing its contribution to soil structure formation, nutrient retention and supply, and water dynamics. These physicochemical improvements are directly linked to enhanced primary productivity and agricultural resilience. Subsequently, it examines the biological mechanisms, highlighting how SOC fuels microbial metabolism and drives the decomposition-mineralization nexus, thereby regulating nutrient cycling and energy flow. A significant portion of this review is dedicated to the climate-regulating function of soil. It analyzes the mechanisms of carbon sequestration and stabilization, discussing the factors influencing the turnover between labile and recalcitrant carbon pools, and its critical feedback to global carbon cycling and climate change mitigation. Furthermore, the review explores the cascading effects of SOC on broader environmental services, including its role in water purification, erosion control, and biodiversity conservation. By integrating findings from biogeochemistry, ecology, and land management science, this review presents a cohesive framework that links molecular-scale interactions of SOC to landscape-level ecosystem outcomes. The review concludes by identifying key knowledge gaps, particularly concerning the responses of different SOC fractions to global change drivers and land-use practices, and emphasizes that the intentional management of soil carbon represents a vital strategy for achieving climate, food, and water security goals in the 21st century.

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# Linking Seasonal Controls and Biological Degradation in the Chihuahuan Desert, Mexico

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## ABSTRACT

Arid and semi-arid ecosystems are often overlooked, yet they play a key role in regulating the variability of the terrestrial carbon (C) sink. These ecosystems are strongly constrained by water availability and are therefore highly sensitive to land-use change. In Mexico, more than 45% of the territory shows signs of human-induced soil degradation, with drylands being among the most affected. This study explores how land use and seasonal rainfall patterns shape soil respiration (Rs) and biological soil degradation in the southeastern Chihuahuan Desert, Coahuila, Mexico.

We evaluated 45 field sites representing five contrasting land uses: conserved shrubland, agricultural crops, livestock grazing areas, walnut orchards, and industrially influenced zones. Thirty-five biotic and abiotic variables were measured, including Rs, soil water content (SWC), microbial biomass carbon (MBC), total carbon, pH, soil texture, and microclimatic conditions. Measurements were carried out during both dry and wet seasons. Rs was quantified using an infrared gas analyzer as an integrative measure of soil biological activity. Structural Equation Modeling and multivariate regression trees were applied to disentangle direct and indirect controls on Rs and to identify sensitive indicators of degradation.

Rs responded to both land use and seasonality. Managed systems showed Rs rates 250–372% higher than conserved shrublands and industrial sites, while wet-season fluxes increased by 145–191% compared to the dry season. Across all land uses, SWC consistently emerged as the dominant control of Rs, highlighting the central role of water in regulating carbon exchange in this dryland system. In contrast, soil temperature exerted a weak and seasonally variable influence. Irrigation and grazing increased water availability and reduced soil pH in managed lands, stimulating MB and accelerating C losses.

By integrating Rs, pH, MBC, and total carbon, we developed a Biological Degradation Index that explained 84% of the variation in soil biological condition, with Rs as the most sensitive indicator. Overall, our results show that land-use change accelerates soil carbon losses in the Chihuahuan Desert and emphasize the need for management practices that conserve soil moisture and organic matter to sustain soil functioning in water-limited environments.

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# Impact of Integrated Agricultural Systems on Soil $CO_2$ Efflux in the Cerrado Biome

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**ABSTRACT**

The adoption of integrated agricultural systems (IAS) in Brazil has become established as a strategy for the restoration of degraded pastures, combining sustainable production with increased local biodiversity through synergistic interactions among production components. However, it is crucial to advance studies that determine the complexity of factors influencing greenhouse gas emissions, considering the diversity of climatic conditions and soil types. This study evaluated soil $CO_2$ efflux and microclimatic conditions across different land-use systems in the Brazilian Cerrado. Seven land use systems were assessed: low-productivity pasture (LPP); well-managed pasture (WMP); consortium of sorghum + marandu grass (CSM); consortium of cratylia + marandu grass (CCM); integrated crop–livestock–forestry system with marandu grass + sorghum + eucalyptus (ICLF1); ICLF with marandu grass + sorghum + eucalyptus + cratylia (ICLF2); and native vegetation of Cerrado (NVC). The variables assessed—soil $CO_2$ efflux, Wflux, soil moisture, and soil temperature—were monitored monthly over a one-year period. Soil temperature, moisture, and Wflux exhibited pronounced seasonal variability, with higher values during the rainy season, which directly influenced soil $CO_2$ efflux, as this period is characterized by enhanced soil microbial activity. Soil $CO_2$ efflux decreased from December to September, with the highest values observed in January (~ 12 µmol $m^{-2}$ $s^{-1}$.), a period characterized by higher soil moisture and temperature, which favored microbial respiration and soil organic matter decomposition. The comparative analysis of the treatments throughout the year showed that NVC exhibited the highest $CO_2$ effluxes (~ 6 µmol $m^{-2}$ $s^{-1}$), whereas the IAS (ICLF1, ICLF2, CSM, and CCM) showed intermediate values (~ 4 µmol $m^{-2}$ $s^{-1}$), suggesting that conservation-oriented management practices using integrated agricultural systems enhance soil quality and improve carbon-use efficiency in the Cerrado biome.

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# Unlocking Carbon Management Sustainability by Quantifying Microbial Necromass and SOC Asynchrony

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**ABSTRACT**

Microbial products and residues are essential for the formation of soil organic carbon (SOC), supporting ecosystem health and contributing to global climate regulation. A key concept in understanding this process is the soil Microbial Carbon Pump (MCP), which emphasizes the role of microbial-derived carbon in the transformation and storage of SOC. Although research on the significance of the MCP in SOC storage has grown rapidly, direct assessments based on this concept remain limited. To address this, we refine key aspects of the MCP by reviewing relevant literature, presenting model scenarios, and offering perspectives on sustainable soil carbon management. We introduce a new metric, △MCP efficacy, which represents the change in the ratio of microbial necromass to SOC. This metric captures the differing responses (asynchronous or synchronous) of microbial necromass and SOC, allowing for the assessment of *in-situ* SOC storage driven by the soil MCP. In this regard, we propose a conceptual, integrated framework that outlines predictable scenarios involving microbial necromass and SOC, illustrating how the soil MCP operates and influences within SOC dynamics. We encourage future research to move beyond quantifying microbial necromass contributions to SOC, and instead focus on evaluating their dynamic, asynchronous changes in magnitude and direction.

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# Global viral auxiliary metabolic genes drive carbon sequestration under climate change

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## ABSTRACT

Soil viral communities play a pivotal role in terrestrial carbon cycling through their regulation of host metabolism. Despite this, the long-term coevolutionary dynamics between viruses and their hosts in response to climatic variations and its implications on carbon sequestration remain poorly understood. Here, we uncover a novel carbon compensation mechanism facilitated by viral auxiliary metabolic genes (AMGs). Employing a cross-climatic zone black soil chronosequence experiment spanning from cold temperate to subtropical zones over 16 years (2005–2021), integrated with the global virus database IMG/VR and multi-omics analyses, we observed a marked enrichment of carbon sequestration-associated AMGs (specifically GT2 and GT4) in viruses under high-temperature conditions. The abundance of these AMGs correlated positively with annual mean temperature and precipitation, exhibiting a 37.8% increase in gene expression post long-term evolution. Protein structure predictions and promoter annotation suggested efficient expression potential of AMGs within host bacteria. Host prediction modeling further indicated that the functional efficiency of AMGs for viral carbon sequestration surpassed 85%, corroborated by transcriptomic evidence. Viral transplantation experiments demonstrated a 26.7% enhancement in carbon sequestration by soil viruses. $^{13}C$ isotope labeling illuminated the role of viral AMGs in facilitating microbial conversion of carbon from both microbial and plant sources into recalcitrant organic matter. Our findings demonstrate that viral activities can counteract climate-driven carbon loss by modulating carbon cycling pathways, providing new insights into phage-host interactions and offering critical implications for predicting terrestrial carbon sequestration under global change.

# Multi-Scale Evidence for Declining Microbial Carbon Fixation Along Forest Succession Gradients

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## ABSTRACT

Microbial involvement in carbon fixation processes can enhance the carbon sink capacity of forest ecosystems, playing a positive role in mitigating global warming. However, there is a lack of large-scale, systematic data necessary to investigate changes in microbial carbon fixation potential and fixation rates during forest succession. We hypothesized that both microbial carbon fixation potential and actual fixation rates would be higher in the early stages of succession compared to later stages, potentially due to greater organic carbon input in younger forest ecosystems. To test these hypotheses, we collected extensive global metagenomic data and conducted a long-term field experiment coupled with $^{13}CO_2$ labelling.

Our results find the following highlights:

(1) Microbial communities—including bacteria, fungi and protists—underwent synchronous succession with vegetation, but microbial carbon fixation potential declined significantly. Vegetation richess, soil organic carbon (SOC), and litter quality were key factors influencing this functional potential.

(2) From global metagenomic datasets, we recovered 253 high-quality MAGs, primarily classified as Pseudomonadota and Actinomycota, which harbored abundant carbon fixation genes. We also found that planted forests had significantly higher carbon fixation gene abundance than natural forests.

(3) The $^{13}CO_2$ labelling experiment confirmed that both microbial carbon fixation potential and actual $CO_2$ fixation rates declined markedly with successional progression.

These findings underscore the ecological importance of microbial carbon fixation in early forest succession, emphasizing its foundational role in initiating soil carbon accumulation and shaping long-term carbon cycling trajectories.

**Acknowledgments**

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# Synergistic regulation of dissolved organic matter and microbial communities on microbial necromass accumulation under long-term organic material application

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**ABSTRACT**

Microorganisms drive soil organic carbon formation primarily through microbial necromass carbon (MNC). This process is regulated by heterogeneous dissolved organic matter (DOM), which induces functional differentiation of microbial communities by serving as energy substrates. However, how the molecular composition and characteristics of DOM regulate microbial community succession and thereby control MNC accumulation remain unexplored, especially under long-term application of organic materials. This study identified the key driving pathways of MNC accumulation using a long-term field experiment initiated in 1990, including chemical fertilizer (CF), CF combined with straw (SCF) or manure (MCF), and an unfertilized control (CK). Results showed that, compared to CK, SCF and MCF significantly increased MNC content by 9.2–38.2%. The application of organic materials (SCF and MCF) transformed labile into refractory DOM through thermodynamically limited process. Moreover, organic materials resulted in fewer labile DOM-bacteria positive networks but more refractory DOM- fungi negative networks, thereby promoting a shift in DOM degradation from rapid bacterial consumption to slower fungal transformation. Further analysis revealed that the SCF treatment promoted fungal network modularity and necromass accumulation by altering the molecular weight of DOM. Whereas MCF treatment enhanced bacterial necromass accumulation by enriching specialized bacterial taxa through DOM with higher aromaticity. Interestingly, the drivers of MNC accumulation shifted from a multi-factor synergy in the 0–20 cm layer to a DOM-dominated (explaining 66.6% of the variation) pathway in the 20–40 cm layer. Overall, our findings highlight the central role of DOM in microbially mediated MNC accumulation and provide mechanistic insights linking DOM characteristics to agricultural management strategies.

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# Patterns and drivers of soil microbial residue carbon responses to precipitation changes in grassland ecosystems

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**ABSTRACT**

Microbial residue carbon (MRC) the response of SOC is a vital component of the soil organic carbon (SOC) pool in grassland ecosystems, regulating the response of SOC to precipitation changes. However, existing studies have largely been confined to individual ecosystems or meta-analyses, yielding no consistent conclusions. There is an urgent need to elucidate the response patterns of soil MRC to precipitation changes and to clarify the underlying driving mechanisms in grassland ecosystems.

We addressed the scientific question based on the China Global Change Network. The experimental network was established in 2017 across alpine and temperate grassland ecosystems, primarily covering alpine meadow, alpine steppe, temperate meadow steppe, temperate typical steppe, and temperate desert steppe. There are three precipitation treatments (decreased 50% precipitation, Control, and increased 50% precipitation), two soil depths (0-10 cm topsoil and 20-40 cm subsoil), and two precipitation duration (short-term three-year precipitation and long-term six-year precipitation).

Our results showed that: 1) Topsoil MRC content ranged from 0.9 to 8.6 g $kg^{-1}$, highest in meadow steppe and lowest in desert steppe. Subsoil MRC content ranged from 0.8 to 4.4 g $kg^{-1}$, higher in meadow and typical steppe, lowest in desert steppe. 2) Short-term decreased precipitation decreased topsoil MRC content by 8%, while short-term increased precipitation reduced soil MRC content by 24%. Under decreased precipitation, diminished plant biomass inhibited soil MRC formation. Increased precipitation induced soil microbial nitrogen limitation, which enhanced soil microbial nitrogen enzyme activity, thereby accelerating soil MRC decomposition and utilization. Compared to drier ecosystems, decreased precipitation resulted in greater soil MRC loss in wetter ecosystems. 3)

Long-term precipitation treatments had no significant effect on topsoil MRC content, indicating that prolonged precipitation changes attenuated the response of topsoil MRC compared to short-term treatments. These results suggest that soil microorganisms exhibit some acclimation to sustained precipitation changes. 4) Under long-term decreased and increased precipitation treatments, subsoil MRC exhibited an asymmetric response pattern and demonstrated greater sensitivity to precipitation changes than the topsoil. Long-term decreased precipitation significantly reduced available nitrogen content, leading to a marked 27.7% decline in MRC, whereas long-term increased precipitation resulted in a slight 10.9% increase in MRC in the subsoil.

Our study reveals that soil microbial residue carbon responses to precipitation changes are shaped by precipitation duration and soil depth, then systematically elucidates the underlying mechanisms, providing a scientific basis for predicting the grassland soil organic carbon pool under future climate change scenarios.

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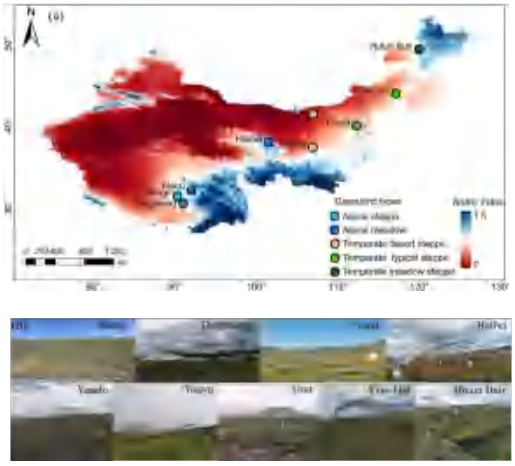


Fig. 1 Geographic locations of the sampling sites (a) and photographs of field precipitation treatment experiments (b).

# Regulation of soil aggregate stability and carbon sequestration by microorganisms under long-term nitrogen and phosphorus application

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## ABSTRACT

Soil aggregates, key soil structural units, act as soil organic carbon (SOC) reservoirs and key microbial colonization sites, but systematic research on their aggregate-scale coupling is limited. This study investigated how long-term nitrogen (N) and phosphorus (P) fertilization regulated SOC and aggregate stability via microorganisms in a meadow steppe. Soil samples under Control, N, P, and NP treatments were collected in withered-yellow (October), green-up (May), and growth (August) period, to analyze SOC, MWD, and microbial communities in bulk soil and aggregates of mega-aggregates, macro-aggregates and micro-aggregates. Results showed that SOC exhibited no significant seasonal variation, with only significant increases observed in May for the bulk soil (NP treatment) and micro-aggregates (P treatment). Micro-aggregate SOC was lower than that of the bulk soil for all sampling times. MWD significantly increased in all months for N and NP treatments (by 16.19%-42.45% for the N treatment, and by 10.00%-19.05% for the NP treatment). Soil microbial biomass exhibits a “peak in May, bottom in October” pattern, and both N and NP treatments generally inhibit microbial activity, with macro-aggregates serving as the core microbial colonization zone. The regulation of SOC by microorganisms was limited to the bulk soil, and there was a overall-scale regulation of MWD. MWD was mainly regulated by arbuscular mycorrhizal fungi (AMF) in the bulk soil, mega- and macro-aggregates, while the role of bacteria in micro-aggregates was enhanced. Microbial contribution to MWD variation peaked in August. In summary, under long-term N and P application, AMF and bacteria respectively dominated the maintenance of stability in different sizes of aggregate. Microbial regulation of aggregate stability exhibited scale dependence and temporal dynamics.

**Key words**: Nitrogen and phosphorus application; Soil aggregate size; Soil organic carbon; Soil microorganisms; mean weight diameter

# Effect of pH Gradient on Microbial Respiration using an Artificial Soil Systems

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**ABSTRACT**

Soil pH is a key factor determining microbial community structure and carbon (C) dynamics. However, the responses of different microbes to soil pH remain poorly understood, as soil pH covaries with nutrient availability and metal toxicity. Therefore, it is difficult to isolate the direct effects of pH. This study aimed to evaluate the effects of altering soil pH as a single parameter on individual microbial species by measuring microbial respiration rates in artificial soil.

Artificial soils were prepared based on previous reports by Ellis (2004) with minor modification. The artificial soils consisted of quartz sand (sand fraction) kaolinite, and bentonite (clay fraction) at a (7:2:1). Humic acid (0.5%) was also used as the pH buffering. The soil pH was adjusted to values ranging from 4 to 9 using 1 M HCl. Eight heterotrophic microbial species were selected from the NBRC culture collection based on their phylum-based life strategies. Each species was inoculated individually into the artificial soil with glucose (C substrate). The inoculated soils were incubated for 10 days at 30 °C, maintaining soil moisture at 20% (w/w). During the incubation, microbial respiration was measured using the MicroResp system (Campbell et al. 2003).

The respiration was suppressed in all species as pH decreased. Based on their response to the pH gradient, species were broadly categorized into three patterns: (i) species whose respiration was sharply inhibited below a specific pH threshold, (ii) species whose respiration was decreased with decreasing with pH, and (iii) species whose respiration was low at all pH ranges. Notably, at pH 7, we observed the strongest negative correlation between cumulative respiration and the genomic traits of GC content and genome size.

This study highlights the diverse and species-specific responses to soil pH. The observed correlations between respiration and genomic traits at neutral pH suggest a link with metabolic potential. This work demonstrates that simplified artificial soil systems are effective tools for isolating and directly evaluating the physiological responses of soil microbes to environmental factors.

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# Differential impacts of moisture fluctuation on dissolved organic matter under different water availability by regulating bacterial network and functional structure

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**ABSTRACT**

Changes in turnover of dissolved organic matter (DOM) influence the stability and storage of soil carbon under global warming (Tao et al., 2024). The understanding of its responses to the climate extremes like drought has advanced in recent years (Shi et al., 2024). Nevertheless, how global warming-induced moisture fluctuation affects the ecological process of DOM, and the underlying mechanisms of this microbe-driven C-cycling remain less known. Our study established a microcosm system to experimentally test the differential impacts of moisture fluctuation under different water availability conditions by regulating the precipitation intensity, precipitation frequency, and evaporation intensity. The results from the 16-week incubation showed that intense moisture fluctuation promoted DOM accumulation with distinct mechanisms. The increased DOM content at drought was likely due to the abiotic processes associated with the weakening in bacterial activity and network complexity, while it was mainly contributed by the enhancement of the activity and metabolism of bacteria at wet condition. Although highly fluctuated moisture substantially inhibited microbial respiration and simplified the network topological structure, such detrimental influence could be compensated when water availability condition was favorable for the bacterial growth. Collectively, these findings demonstrated that the ecological process of DOM was regulated by the interactive effects of average and fluctuation of soil moisture condition, highlighting the importance of considering fluctuation pattern in understanding the microbe-driven DOM turnover in the context of climate change.

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# Changing from divergence to convergence between soil microbial communities derived from intracellular and extracellular DNAs along a hydrothermal gradient on the Tibetan Plateau

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**ABSTRACT**

Distinguishing intracellular DNA (iDNA) from extracellular DNA (eDNA) is essential for accurately interpreting soil microbial patterns and understanding the dynamics of microbial living and dying, especially in ecosystems where relic DNA accumulates. In this study, we characterized iDNA and eDNA derived soil microbial communities to assess the pattern and driving factors of living and relic components along a pronounced hydrothermal gradient across the Tibetan Plateau.

The cold–dry regions showed exceptionally high eDNA proportions, often exceeding 50% of total soil DNA, indicating strong historical accumulation under extreme water limitation. In parallel, the two DNA pools displayed divergent ecological drivers: iDNA diversity was mainly governed by temperature, nutrient availability, and ecosystem productivity, whereas eDNA richness was more strongly associated with aridity and soil texture. NMDS analysis further revealed clear separation between iDNA and eDNA communities, with the divergence intensifying in cold–dry sites, where eDNA contained numerous ASVs absent from the active community. In contrast, warm–humid sites exhibited greater convergence between iDNA and eDNA, suggesting that extracellular DNA in these regions reflects more recent biological inputs due to faster turnover. Distance–decay analysis showed steeper spatial structuring in eDNA, highlighting preserved historical biogeographic signatures, while iDNA captured contemporary environmental filtering.

Together, these results demonstrate that iDNA and eDNA encode distinct temporal and ecological information, corresponding to active and historical microbial states. Separating the two pools is therefore critical for resolving microbial biogeographical patterns, interpreting environmental responses, and identifying ecological interactions. This distinction provides a mechanistic foundation for understanding how microbial living and dying shape soil carbon processes across heterogeneous and climate-sensitive alpine landscapes.

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# Soil microbial community structure and soil carbon dynamics in fields and hedgerows of Northern Irish Grasslands

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**ABSTRACT**

It is estimated that global grasslands store 236 giga tons of carbon (C) in soil belowground, playing an important role in global climate change mitigation. This is particularly important for Northern Ireland (NI) where grasslands cover ~95% of farmland. As part of Soil Nutrient Health Scheme (SNHS) project we selected 257 grasslands across NI, representing wider active grassland management practices across NI, and are measuring soil C stocks, nutrients, carbon lability, age of carbon via radio carbon dating and microbial community structure (MCS) via phospholipid fatty acid analyses up to 30 cm depth, extending to 1 m depth which is currently ongoing, sampling both within the farm and nearby hedgerows. Our results show that grassland MCS is dominated by Gram-negative bacteria, and it significantly varies with depth, and between fields and hedgerows. Actinobacteria ($P<0.001$), Gram-positive ($P<0.001$) and fungi ($P<0.001$) showed greater relative abundance in fields soils, while other bacterial ($P<0.001$) and unclassified ($P<0.001$) fatty acids showed greater relative abundance in hedgerow soils. Fungi:bacteria and Gram-positive:Gram-negative ratios were greater in field soils, whilst other fatty acid ratios that were used as stress indicators were greater in hedgerow soils. Soil MCS is also significantly affected field/hedgerow topography and showed no seasonal effects. Microbial biomass was greater in the field than hedgerow soils. C and nitrogen (N) content in hedgerow soils were greater than nearby farm soils, showing significant interactions with topography and soil microbial community structure. Our preliminary results show significant increase in C and N stocks from the year 2004 to 2024, indicating C sequestration in NI farms over the last two decades. Currently, we are analysing the samples for MCS to full soil depth (up to 1m) and exploring the relationship between soil microbial community structure and carbon dynamics in these grasslands. Findings from our research will provide important insights into grassland carbon sequestration and sustainable land management for NI.

**Acknowledgments**

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# Time-scale dependent responses of microbial carbon use efficiency to warming in alpine soils on the Qinghai-Tibetan Plateau

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## ABSTRACT

Soil microorganisms regulate terrestrial carbon (C) cycling by partitioning assimilated C between respiration (R), growth (G), and carbon use efficiency (CUE). Yet how microbial C allocation responds to warming across distinct temporal scales remains unclear. We combined a long-term elevation gradient (3200–4000 m), a decade open-top chamber (OTC) warming experiment, and a short-term +10 °C incubation to quantify how different time-scale warming shape R, G, CUE, and their temperature sensitivities (Q10) on the Qinghai–Tibetan Plateau.

Warming effects were strongly time-scale dependent. Along the elevation gradient, moderate thermal and nutrient conditions enhanced G more than R, producing the highest CUE at mid-elevation, whereas both warm and cold sites exhibited reduced CUE due to nutrient depletion or physiological constraints (Broderick et al., 2025). Medium-term OTC warming increased CUE at the cold site but suppressed it at warmer sites, indicating that historical climate and resource availability modulate microbial adaptability (Ren et al., 2024). Short-term warming consistently stimulated R while failing to proportionally enhance G, leading to universal CUE declines (Bian et al., 2022).

Mass-specific responses showed that warming shifted the balance between catabolism and anabolism. Short-term warming increased maintenance respiration and shortened microbial turnover, while phosphorus availability and soil physical structure moderated anabolic capacity and microbial persistence (Spohn et al., 2016). Q10 values varied widely: Q10_G showed the strongest variability and was the principal driver of Q10_CUE. CUE increased when G was more temperature-responsive than R and declined when respiration dominated, reflecting inherent trade-offs between metabolic pathways (Tao et al., 2023). Our findings demonstrate that microbial CUE is not a fixed parameter but a dynamic, trait-like property shaped by multi-temporal warming, nutrient stoichiometry, and soil structure.

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# Fenton reaction facilitates chitin degradation and nitrogen acquisition in the ectomycorrhizal fungus Suillus luteus

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**ABSTRACT**

Chitin is one of the most abundant nitrogen containing polymers in forest soils. Previous work showed that the ectomycorrhizal (ECM) fungus including *Suillus luteus* can efficiently liberate nitrogen from exogenous chitin (Maillard et al., 2023). However, the data did not support the actions of classical chitin-degradation pathways involving hydrolytic and oxidative enzymes. Using tightly controlled spectroscopic, isotopic, transcriptomic and chemical experiments, we here demonstrate that *S. luteus* degrade chitin using an oxidative mechanism including the action of hydroxyl radicals ($HO^{\bullet}$) generated by Fenton chemistry ($Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + HO^{\bullet} + OH^-$). Collectively, our experiments suggest that Fenton chemistry is driven by extracellular fungal metabolites that reduce $Fe^{3+}$ bound to glucosamine residues in the chitin substrate. The $H_2O_2$ generated by fungal activity initiates a localized Fenton reaction. The resulting $HO^{\bullet}$ radicals target the amino groups of glucosamine, leading to the release of ammonium, which is taken up by the fungus. $HO^{\bullet}$ oxidation also destroys the crystalline structure and polymeric chains of the chitin substrate. Concomitant with oxidation, the fungus secretes chitinases and β-N-acetylglucosaminidases, suggesting that Fenton oxidation works in concert with hydrolytic enzymes. Taken together, we propose a novel fungal pathway for chitin degradation that is similar to the Fenton-based mechanism used by saprotrophic brown-rot fungi to degrade cellulose.

**Acknowledgments**

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# Soil microbial life-history strategies covary with ecosystem multifunctionality across aridity gradients

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## ABSTRACT

Aridity thresholds shape ecosystem functions worldwide. Despite the importance of soil microbiomes in engineering ecosystem processes, the specific strategies employed by soil microbiomes to support ecosystem multifunctionality (EMF) across aridity gradients remain virtually unknown. Here, we investigated 474 soil samples across a continental-scale aridity gradient and identified an aridity threshold beyond which plot-level EMF declines sharply. Microbial habitat and decomposition functions were among the last to respond to aridity, with thresholds occurring under more arid conditions compared to plant productivity and soil fertility. Combining metagenomic sequencing with physiological assays to characterize microbial life-history strategies of high yield (Y), resource acquisition (A), and stress tolerance (S), we introduce a microbial trait-based framework to mechanistically link community-level microbial life-history strategies to ecosystem multifunctionality. Our results reveal that microbial Y-strategy is positively correlated with EMF across aridity gradients, A-strategy exhibits a negative association with EMF across aridity gradients, and S-strategy is negatively correlated with EMF in arid ecosystems. Collectively, this study offers empirical evidence and novel insights into how aridification interacts with soil microbiomes in shaping EMF, highlighting the pivotal role of microbial life-history strategies in understanding the mechanisms behind EMF variation in an increasingly arid world.

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# Resolving the microbial processes underpinning necromass pools across landuses

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## ABSTRACT

Microbial necromass is thought to form a key component of the persistent soil carbon stock, and production and consumption rates should equate with stocks estimated with amino sugars. We tested this in soils from grasslands, croplands, and forests from Luxembourg and Sweden. In soil incubations, we quantified production as growth rate of, consumption as mining rate on, $^{13}$C-necromass substrate generated from bacteria (*Bacillus licheniformis*) and fungal (*Trichoderma harzianum*), and compared the differences in these rates to necromass stocks as estimated from amino sugars. On average, the growth rate of microbial biomass after adding fungal necromass was 9.3 times that of adding bacterial necromass. The carbon utilization efficiency of fungal necromass is also higher than that of bacterial necromass. Although there was also high fungal mining, rates were much lower than growth rates. The decay rates of fungal and bacterial necromass were 0.44 and 0.40 ng $g^{-1}$ $h^{-1}$. Bacterial necromass was more susceptible to variations in soil conditions compared to fungal necromass. Amino sugars were also dominated by fungal necromass (>90%) and as a result, the relationship between net necromass (production-consumption, growth rate-decay rate) correlates positively with necromass stocks as calculated from amino sugars. Our hypothesis that the difference between rates of production and consumption would predict necromass stocks was supported, largely determined by the faster growth on fungal necromass. This insight could inform broader ecological models, even climate change mitigation strategies by highlighting the importance of microbial necromass in nutrient cycling and C dynamics.

# Microbial sequestration pathways of soil organic carbon in meadow steppes under long-term nitrogen and phosphorus application: Analysis based on aggregate scale residual carbon

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**ABSTRACT**

The regulation of microbial residue carbon (MRC) in soil aggregates, a key component of stable soil organic carbon (SOC), remains poorly understood under nitrogen (N) and phosphorus (P) deposition. Based on a 14-year nitrogen and phosphorus addition field experiment on meadow grassland, we systematically analyzed the seasonal dynamics of MRC, microbial biomass, and SOC across aggregate size classes (LMA: >2 mm, SMA: 0.25-2 mm, MI: <0.25 mm) to elucidate how long-term N and P application alter the contribution of aggregate-scale microbially mediated MRC to SOC. The results indicate that SOC content did not exhibit significant seasonal variation, with significant increases observed only in May for bulk soil under NP treatment and MI under N treatment. MRC responses to nitrogen and phosphorus varied by season and particle size. in October LMA, MRC increased significantly by 17.80% under N treatment, whereas NP treatment reduced MRC content across multiple particle-size fractions in May and August (decreases of 11.41%–15.59%). Fungal residue carbon consistently contributed more to SOC than bacterial residue carbon across all treatments, seasons, and particle sizes, driving MRC dynamics. N and NP treatments consistently suppressed microbial biomass across aggregate sizes. The SMA emerged as a critical niche for microbial activity and MRC accumulation, attributed to its structure and carbon availability. Notably, MRC accumulation and its contribution to SOC peaked in August but were lowest in May, contrasting with microbial biomass, which peaked in May and troughed in October. This asynchrony indicates that MRC buildup reflects seasonal coordination between microbial turnover and soil protection mechanisms rather than biomass alone. Specifically, in October, N and NP treatments increased MRC in SOC by inhibiting microbial growth and residue decomposition, leading to a rise in MRC as microbial biomass decreased. In May and August, MRC's contribution to SOC was linked to microbial biomass, showing dependence on residue production rates. These findings highlight that long-term N and P application differentially regulate the contribution of MRC to SOC across aggregate size classes and seasons, offering insights for precise grassland carbon sequestration management.

**Key words**: Long-time nitrogen and phosphorus application; Soil aggregate size; Microbial residue carbon; Soil microorganisms; Seasonal

**Acknowledgments**

We thank the Research and Monitoring Institute of Environmental Protection of the Ministry of Agriculture and Rural Affairs for their great support in the field work. This study was funded by the National Natural Science Foundation of China (nos. 32460315 and 32503289) and The Basic Scientific Research Business Expenses Project of the Directly affiliated universities of the Inner Mongolia Autonomous Region (nos. BR251022).

# Viral mediation of microbial turnover governs soil organic matter allocation

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**ABSTRACT**

Soil organic matter (SOM) persistence depends on how plant inputs are transformed by microbial growth and mortality, yet depth patterns in SOM composition are rarely connected to viral control of microbial turnover. We integrate 0–100 cm paddy soil profiles quantifying plant- vs microbial-derived C with 1824 soil metagenomes from eight biomes to test whether viral regule SOM allocation. In paddy soils, topsoil (0–40 cm) was enriched in carbohydrate- and lignin-like fractions (38–50%), whereas subsoil (40–100 cm) contained more protein- and lipid-like fractions (26–60%). With increasing SOM, plant-derived C rose while microbially derived C declined; the microbial-to-plant C ratio decreased 23–30% faster in topsoil than subsoil. Plant C input and temperature best explained topsoil variation, whereas the fungi:bacteria ratio and clay content dominated subsoil controls. Globally, soil viromes were dominated by lytic strategies (88%; Siphoviridae 35.34%) and were associated with lower microbial carbon use efficiency (CUE) and higher necromass, consistent with viral-mediated mortality redirecting C from growth to necromass pathways. CUE emerged as the strongest predictor of microbially derived C, with lytic viruses exerting a larger direct contribution (3%) than lysogenic viruses (1%). Overall, our results identify viral-driven microbial death as a key mechanism connecting depth-specific drivers to SOM allocation and long-term carbon preservation

# Protist predation shifts bacterial life strategies and increases carbon use efficiency across contrasting soils

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**ABSTRACT**

Microbial carbon use efficiency (CUE) helps determine whether organic carbon is retained in soil as microbial biomass or returned to the atmosphere as $CO_2$. Protists are common bacterial grazers in soils, but their effects on carbon use efficiency, and the mechanisms involved remain poorly understood. We examined the effects of protist predation in two typical agricultural soils with different nutrient levels (Mollisol and Ultisol) using metagenomics, carbon catabolic fingerprints, and physiological measurements. Protist predation altered bacterial community composition differently in the two soils, yet it drove similar shifts in carbon catabolic fingerprints across soils. Metagenomic analyses indicated that predation was associated with reduced resource-acquisition functions (A-strategy) and enhanced biosynthesis and yield-oriented functions (Y-strategy). In line with this pattern, functions involved in biosynthesis and core metabolism increased, whereas traits linked to resource acquisition, including motility and siderophore production, decreased. CUE increased under predation, especially in Ultisol, and this was accompanied by higher microbial biomass carbon and lower respiration-related indicators. Predation also reduced activities of key carbon-degrading enzymes and decreased the inferred potential for organic carbon decomposition based on CAZyme functions, with distinct responses between the two soils. Together, our results highlight protists as important regulators of bacterial physiology and suggest that predator-driven shifts in bacterial functional traits can influence soil carbon cycling.

**Keywords:** Soil protists, Carbon use efficiency, bacterial life-history strategies

**Acknowledgments**

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# Clay-organic matter interactions drive microbial necromass preservation in soils

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**ABSTRACT**

Microbial necromass is increasingly recognized as a major source of stable soil organic matter (SOM), and its persistence is often attributed to interactions with clay-sized minerals. However, the mechanisms by which these mineral associations stabilize necromass remain poorly understood. Here, we conducted an in situ dual-labelled ($^{13}C$ and $^{15}N$) microbial necromass experiment across a clay gradient to quantify how clay content and necromass type (bacterial vs. fungal) regulate its persistence. We found that higher clay content markedly enhances necromass retention by increasing mineral protection, suppressing microbial activity and diversity, and limiting leaching loss. The NanoSIMS imaging showed that newly added necromass preferentially associates with organic matter coating the rough mineral surfaces, highlighting organo-organic interfaces as dominant stabilization pathways. Necromass origin has little effect on retention, even though bacterial and fungal necromass differed in their C:N ratios and bulk chemical composition. This further suggests that finer-scale molecular features, rather than these broad compositional differences, may govern necromass stabilization in soil. Together, these findings reveal how clay-sized minerals modulate multiple protection and loss pathways to determine necromass persistence, providing mechanistic insight essential for improving predictions of SOM dynamics.

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# Soil organic matter persistence emerges from recursive microbial necromass and mineral feedbacks

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**ABSTRACT**

Soil organic matter (SOM) constitutes the largest terrestrial carbon pool, yet its dynamics remain poorly predicted by current Earth system models that partition SOM into mineral- and aggregate-mediated pathways based on litter chemistry, largely overlooking microbial contributions to long-term persistence. We show that while fine litter contributes to both pathways, SOM persistence emerges from a recursive microbial necromass–mineral cycle. Litter-derived microbial necromass initiates organo-mineral aggregation, shifting microbial metabolism from substrate-selective bacterial assimilation to fungal-mediated, non-selective SOM catabolism. This reprogramming sustains the cycle, generating recursive microbial–structural–stoichiometric feedbacks that progressively convert particulate organic matter into a stable yet dynamically recycling mineral-associated pool. When disrupted—often due to stoichiometric imbalance—these feedbacks intensify microbial competition and accelerate carbon loss, particularly in long-cultivated soils with degraded resilience. Our framework establishes iterative microbial life–death cycles within plant-derived microsites as the central engine of SOM dynamics, resolving long-standing SOM paradoxes and providing a mechanistic, process-explicit foundation for understanding the soil–microbe ecosystem as self-organizing, thereby improving carbon–climate projections and guiding resilience-focused soil stewardship.

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# Urban soil virus homogenization reshapes microbial organic matter decomposition and carbon sequestration potential

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## ABSTRACT

Urban areas cover less than 0.6% of the Earth's land surface yet account for over 70% of global energy-related $CO_2$ emissions. Soil viruses, with populations up to $10^{10}$ per gram of soil, play a vital role in regulating microbial communities and the carbon biogeochemical cycle. Although the global patterns of soil viruses have been well established in natural ecosystems, few studies have explored urban soil viruses and their roles in carbon cycling. Here, we used a global database of paired urban greenspaces and natural ecosystems in 27 cities from 17 countries across six continents encompassing broad variation in SOC stocks and quality. We analyzed the distribution of soil viruses and their contributions to soil organic carbon pools in urban and natural ecosystems. Urban greenspaces exhibited reduced soil viral diversity and significant community homogenization, forming a subset of the viral pool found in natural ecosystems. Virus-host interaction analysis revealed that only 4.5% of vOTUs could be linked to microbial hosts (MAGs), with natural ecosystems harboring more virus-host pairs than urban greenspaces. In addition, there are obvious differences in the pattern of virus-mediated organic carbon regulation between urban green spaces and natural ecosystems. Viral abundance showed stronger negative correlations with bacterial genes involved in chitin, cellulose, pectin, and hemicellulose degradation in urban soils, suggesting urban conditions may favor viral proliferation over these specific decomposer communities. While natural ecosystems maintained higher AMG diversity, urban greenspaces exhibited significant enrichment of viral glycosyltransferase genes (particularly GT2 and GT4), indicating enhanced viral contributions to carbon sequestration. Our results reinforce the importance of soil viruses in supporting urban soil carbon sequestration, offering potential microbial-oriented strategies for the conservation of urban soil carbon pools and the capacity of improve global C cycle models.

**Keywords:** Urban greenspaces, Soil viruses, Homogenization, Soil carbon pools

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# Microbial Enhancement of Soil Inorganic Carbon and Its Synergy with Organic Carbon Stabilization

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**ABSTRACT**

As the largest terrestrial carbon reservoir, soil plays a critical role in the global climate system. Soil inorganic carbon (SIC) has traditionally been regarded as more stable than soil organic carbon (SOC). However, growing evidence challenges this perspective, indicating a widespread decline in SIC stocks. Current approaches to enhance SIC primarily include silicate weathering enhancement and biochar application. Beyond these, specific microorganisms can induce carbonate precipitation through metabolic processes such as photosynthesis, urea hydrolysis, and sulfate reduction. To investigate SIC enhancement and its interaction with SOC, a microcosm experiment was conducted using carbonate-precipitating microorganisms. This study integrated analyses of soil carbon fractions, stable isotope measurements, and microbiome profiling. Inoculation with microorganisms increased soil inorganic carbon content by 2.41 mg/g and 1.85 mg/g in alkaline and acidic soils, respectively. Furthermore, treatments with higher SIC content exhibited increased mineral-associated organic carbon (MAOC). These findings advance the understanding of soil carbon sequestration mechanisms and support the development of sustainable soil management strategies for climate change mitigation.

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# Thermal adaptation reshapes soil microbial carbon use efficiency under prolong warming

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**ABSTRACT**

Thermal responses of microbial carbon use efficiency (CUE) to warming remain a major uncertainty in predicting soil-climate feedbacks. Long-term studies have reported variable outcomes, including decreases, increases or no detectable change, reflecting the interacting influences of microbial physiological adaptation and resource availability. Here, in a five-year in situ warming experiment, we resolved these inconsistencies by statistically isolating the direct physiological responses from co-varying environmental factors. We found that microbial CUE follows a non-monotonic adaptive trajectory, shifting from an initial suppression to a subsequent enhancement. Importantly, the direct warming effect on CUE strengthens over time, indicating that microbial growth adaptation outpaces compensatory adaptation in respiration. This community-level adaptation is associated with an ecological selection for higher metabolic efficiency, with functional gene composition emerging as a stronger predictor of the CUE thermal response rather than microbial taxonomic composition. Integrating observed CUE dynamics into a biogeochemical model improved prediction of the labile organic carbon pool, confirming the importance of the thermal adaptive process. Our findings clarify the long-term thermal response of microbial CUE and show that the initial physiological decline can be offset by growth adaptation. This highlights the need for Earth system models to incorporate the thermal adaptation of microbial physiological traits to accurately predict future soil carbon dynamics.

**Keywords:** Microbial carbon use efficiency; Long-term warming; Physiological thermal adaptation; Substrate availability; Soil carbon modeling

# Influence of nitrogen fertilization and cover crops on soil microbial dormant fraction

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**ABSTRACT**

Soil microbial communities play a crucial role in nutrient cycling and ecosystem functioning, with their activity being heavily influenced by environmental factors such as cover cropping and nitrogen fertilization. This study investigates the interactive effects of cover crop types and nitrogen fertilization on the soil microbial dormant fraction, focusing on the changes in microbial activity during different nitrogen levels and cover crop systems. Through a two-year field experiment, we assessed the impact of various cover crop treatments (no-cover, soybean monoculture, Sudan grass monoculture, and mixed cover crop) under different nitrogen fertilization levels (0, 60, and 120 kg/ha) on microbial dormancy. Our results demonstrate that the mixed cover crop treatment significantly reduced the microbial dormant fraction compared to monoculture systems, highlighting its potential for enhancing microbial activity. Additionally, nitrogen fertilization, especially at higher levels (N120), further suppressed microbial dormancy, indicating that nitrogen availability is a key driver in the activation of dormant microbial populations. Variance partitioning analysis revealed that the regulatory mechanisms differed across cover crop systems, with nutrient availability playing a dominant role in mixed cover crops. These findings suggest that combining appropriate cover crop management with optimized nitrogen fertilization strategies can effectively stimulate soil microbial activity, promoting healthier soils and improving nutrient cycling efficiency. This research provides insights into how agricultural practices can be tailored to activate soil microbial communities, potentially boosting crop productivity and advancing sustainable farming practices.

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# Response of Microbial Necromass and Extracellular Polymeric Substances under Multifaceted Global Change

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**ABSTRACT**

Increasing frequency of extreme climate events is posing a significant threat to soil ecosystems, including microbial life and functions. Because soil microorganisms are sensitive to environmental perturbations, leading to shifts in the composition and stability of microbial-derived carbon pools. Microbial necromass, commonly identified by amino sugars, is accumulated through microbial growth and turnover and thereby contributing to stable soil organic carbon. While extracellular polymeric substances (EPS) are actively secreted, this requires high-cost investment by microorganisms. Whether such intracellular and extracellular microbial strategies in carbon allocation can be regulated over time, to meet their survival or resource needs under environmental stress, is largely unknown.

Here, we studied the interannual variability in the dynamic changes of soil microbial-derived carbon under two long-term experiments that manipulated extreme drought and sustained warming in a subtropical forest. We quantified soil amino sugars and EPS, characterized their major compositional components, and linked their dynamics to changes in soil organic carbon and microbial communities. Our results reveal distinct responses of EPS and microbial necromass to different global change scenarios across years. Under extreme drought, compared to the weak response of microbial necromass, EPS exhibited strong interannual dynamics, suggesting that microorganisms primarily adjust extracellular carbon allocation to cope with extreme water shortage. In contrast, sustained warming markedly shaped microbial necromass over time, but hardly influenced EPS, indicating that warming predominantly regulates microbial growth–death turnover processes and the subsequent accumulation of microbial residues.

Overall, our results demonstrate different microbial mechanisms resulting in contrasting dynamic changes in intracellular and extracellular microbial-derived carbon responses to extreme drought and sustained warming, with important implications for soil organic carbon turnover and stabilization. Our findings highlight the essential role of soil microorganisms in mediating different microbial-derived carbon pools amid escalating extreme climate.

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# Pathway-aware microbial phosphorus traits predict carbon-use efficiency and soil organic carbon turnover across urban gradients

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**ABSTRACT**

Microbial growth and necromass formation are central to soil organic carbon (SOC) stabilization, but they are frequently constrained by phosphorus (P) supply and by the specific pathways microbes use to access organic and mineral P. We tested whether a pathway-aware index of microbial P-acquisition traits (EPSI; integrating *pqq*-dependent phosphatase systems and P transport/assimilation modules) can predict carbon-use efficiency (CUE) and SOC turnover across urban–peri-urban gradients. Soils will be sampled along replicated transects spanning dense urban greenspaces, peri-urban forests, and adjacent croplands, capturing contrasting P forms (labile vs. occluded) and mineral protection capacity. We quantified SOC fractions (particulate vs. mineral-associated), microbial biomass and necromass proxies, extracellular enzyme stoichiometry (C:N:P), and gross C mineralization in standardized incubations with factorial P addition and substrate pulses. Metagenomic and qPCR assays provided EPSI and key functional-gene abundances. We hypothesized that (i) higher EPSI buffers microbial P limitation, increasing CUE and shifting carbon allocation from enzyme production toward biomass growth; (ii) this promotes greater microbial necromass contribution to mineral-associated organic matter, reducing SOC vulnerability; and (iii) EPSI will outperform bulk soil P metrics in explaining spatial heterogeneity of SOC turnover. By explicitly linking microbial P pathways to carbon processing, this work offers a scalable trait-based lever for improving SOC predictions under urbanization and nutrient management.

**Keywords:** microbial phosphorus acquisition; carbon-use efficiency; soil organic carbon turnover; necromass stabilization; urban gradient

# From expansion to endurance: persistent warming reshapes soil active microbial communities in forest ecosystems

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**ABSTRACT**

Climate warming strongly influences soil microbial activity, yet how soil active microbial communities respond to persistent warming over multi-year time scales remains unclear, particularly in forest ecosystems. Here, we examined responses of soil active microbial communities to persistent warming spanning 3–5 years using a reciprocal soil translocation experiment in the Qinling Mountains, China. Soil microbial activity and functional dynamics were assessed using a combined 16S rRNA/DNA approach and metatranscriptomic analyses. The proportion of active soil microorganisms increased by 14.77% after three years of warming, indicating an early expansion phase with enhanced microbial activity and growth. In contrast, five years of persistent warming significantly reduced active microbial proportions (−20.28%) and markedly altered community composition. Metatranscriptomic results indicate that prolonged warming favors an endurance-oriented strategy, with increased investment in maintenance, stress tolerance, and resuscitation potential, coupled with reduced allocation to growth-related and resource-intensive pathways. Together, these findings reveal a directional transition of soil active microbial communities from expansion to endurance under persistent warming. Overall, our results demonstrate strong time-dependent responses of soil active microbial communities to warming, highlighting the importance of temporal dynamics when assessing microbial-mediated soil carbon processes under climate change.

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# Microbes as engineers in modulating and preserving soil organic carbon

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**ABSTRACT**

There has been growing recognition on the central roles of microorganisms in the cycling and preservation of soil organic carbon under the regime of soil health deterioration and the dire situation of global climate change. Investigation on microbial $CO_2$ sequestration at large scale shows that $CO_2$ fixation rates in soils are highly correlated with the community composition of autotrophic bacteria and phototrophic protists. Paddy soils, supporting a larger proportion of obligate bacterial and protist autotrophs, display four-fold of $CO_2$ fixation rates over upland and forest soils. On the other hand, microbial biomass and necromass mediate the formation of various organic carbon pools in soils. Although microbial necromass carbon per se accounts for only 41- 44% of mineral associated organic carbon (MAOC) in soils of various ecosystems, MAOC accumulation is primarily regulated by microbial activity. The degradation, turnover and accumulation of organic carbon by microbial processes are profoundly influenced by their interactions with clay minerals, land utilization and environmental parameters. Clay minerals are not only the microbial habitats, but also suppress or enhance microbial growth and activity via a range of physical and chemical processes, ultimately regulating the cycling and preservation of soil organic carbon. The interplay mechanisms between microorganisms and minerals have been studied extensively over the past years. However, their impacts and contributions to the long-term storage of soil organic carbon have largely been unknown. Further studies are required to evaluate and quantify microbial contribution to soil stable C pool and to parse the in-depth mechanisms of microbial processes and their interactions with minerals in soil carbon accrual from microscale to different landscapes by virtue of various chemical, spectroscopic and microscopic techniques, and modelling. Incorporation of microbial indices such as physiological, biological attributes and functional genes and also their interactions with soil minerals in the modelling of soil organic carbon will improve the Earth System Model.

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# Effects of repeated freeze-thaw cycling on microbial activity in a temperate forest soil

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**ABSTRACT**

Freeze-thaw events represent an important phenomenon in terms of soil hydrology and thermodynamics. The change in environmental conditions associated with these events may induce stress within the soil microbial community. Previous studies have shown freeze-thaw cycles increase DOC concentrations. The increase of DOC in soil may be associated with microbial death or the release of cryoprotectants (osmolytes) into soil solution. Surviving microbes can then take up the DOC and release $CO_2$ via respiration, with important implications for soil carbon storage and greenhouse gas emissions.

Some studies have shown most microbial damage by freeze-thaw occurs within the first 1 or 2 freeze-thaw cycles. In this study, we investigated the effect of repeated (3 times) freeze-thaw cycles on soil microbial communities, and to see whether repeated freeze-thaw cycles have a cumulative effect relative to a single freeze-thaw event. We observed that DOC, TDN, amino acids and $NH4^+$ increased on thawing from both single and repeated severe freeze-thaw events, and that the effects of repeated freeze-thaw events were greater than a single freeze-thaw cycle. Soil metabolomes changed after both freeze-thaw events. A single severe freeze-thaw recovered soil metabolomes within 5 days whilst repeated severe freeze-thaw did not recover at all.

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# Vertical distribution and controlling factors of soil microbial necromass carbon (MNC) under erosion–deposition processes

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**ABSTRACT**

Soil organic carbon (SOC) stability is essential for ecosystem function in eroded landscapes. Erosion reshapes soil carbon dynamics by depleting surface SOC in erosion zones, supplying fresh carbon to depositional areas, and altering soil microenvironments that regulate microbial necromass carbon (MNC), a major contributor to SOC stability. However, the vertical distribution of MNC and its controlling factors in erosion and depositional environments remain unclear. We investigated 4-m-deep soil profiles from erosion and depositional zones on the Loess Plateau to determine how erosion shapes vertical distribution and controls of MNC. The MNC/SOC ratio generally exceeded 50%, indicating MNC is a major SOC component. MNC showed strong vertical stratification in erosion zones (Topsoil > Subsoil > Deepsoil), while depositional zones had weaker vertical differentiation with more accumulation in deepsoils, reflecting lateral transfer and burial. Additionally, Microbial factors were the main drivers of MNC accumulation. In erosion zones, topsoil MNC was mainly influenced by bacterial composition and microbial biomass, while deepsoil MNC was controlled by multiple microbial groups and their functions. In depositional zones, microbial regulation was more localized, primarily influencing deepsoils. Our results suggest that erosion-induced redistribution and burial of MNC are crucial for its vertical organization and long-term SOC stabilization.

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# Microbial respiration, growth, and CUE - The roles of Land use, management, and environmental factors

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## ABSTRACT

Microbial growth and carbon use efficiency (CUE) are central to soil organic carbon (SOC) cycling as they control the formation of microbial residues that can become stabilized and contribute to persistent SOC pools. Land use and its intensification are known to affect above- belowground biodiversity and functions, thereby modifying the role of microbial traits in SOC formation. However, it remains unknown how changes in the quantity and quality of plant litter input, or management, influence microbial physiological traits, and how these changes interact with SOC persistence at a quantitative and mechanistic level. Within the Biodiversity Exploratories framework which was established since 2006, we present an integrated assessment of how land-use type, management intensity, and soil properties regulate microbial physiological traits and their implications for SOC quantity and potential quality in grassland and forest soils across 300 plots in three different regions in Germany. Grasslands exhibited significantly higher total microbial growth and respiration, as well as higher specific respiration, but showed no differences in CUE compared to forests. In forest ecosystems, tree species identity exerted strong effects on microbial physiology, with deciduous stands exhibiting higher microbial growth and CUE than coniferous stands. Management intensity in grasslands, particularly nitrogen inputs, exerted positive indirect effects on microbial growth and carbon use efficiency (CUE), whereas in forests, management had predominantly negative effects on CUE, acting both directly and indirectly through changes in abiotic soil properties. Across ecosystems, microbial biomass carbon and soil pH emerged as key regulators of microbial physiological traits in forests, while grasslands showed more dynamic responses, likely reflecting stronger controls by resource availability and limitation in managed systems. Overall, our findings demonstrate that microbial carbon dynamics are governed by distinct regulatory mechanisms across land-use types and management regimes.

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# Optimizing Soil Carbon Sequestration: Microbial Regulation by Straw Return Quantity and Frequency

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**ABSTRACT**

Enhancing soil organic carbon (SOC) sequestration through crop straw return is a critical strategy for sustainable agriculture and climate change mitigation. However, the synergistic mechanisms through which straw quantity and application frequency jointly regulate microbial life-history strategies and ultimately drive SOC formation and persistence remain inadequately understood. This study integrates findings from two complementary field experiments in black soil regions to address the questions of "how much" and "how often" straw should be returned to maximize SOC accrual. Our results demonstrate that while any straw return increases microbial biomass and diversity, only an optimal quantity (approximately 67% of generated straw) efficiently couples rapid microbial response with long-term carbon transformation processes, leading to the highest continuous conversion efficiency from microbial biomass to necromass and, consequently, the greatest SOC accumulation. Simultaneously, we found that high-frequency straw application reshapes the microbial community toward a more copiotrophic-dominated assembly, fosters a more complex and tightly connected ecological network, and diversifies potential functional traits. This "little and often" strategy minimizes nutrient waste and enhances the efficient channeling of microbial biomass into stable residual carbon. By integrating these findings, we propose a novel Microbial Efficiency-Framework for straw management. This framework posits that the interactive effects of optimal quantity and high frequency synergistically steer microbial communities toward strategies that maximize the efficiency of the "microbial growth-to-necromass" pipeline, thereby optimizing the SOC sequestration potential. This work provides a mechanistic basis for precision straw management in black soil conservation and offers actionable insights for achieving agricultural dual-carbon goals.

**Keywords:** soil organic carbon, tillage, stover mulching, microbial community, microbial necromass carbon

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# Soil arbuscular mycorrhizal fungi mediate the contribution of microbial necromass carbon to soil organic carbon in rocky desertification areas

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## ABSTRACT

The soil carbon dynamics in karst ecosystems were an important component of the global terrestrial carbon cycle. Microbial necromass carbon played a crucial role in the accumulation of organic carbon. Determining the microbial necromass carbon content in different forest soils and exploring the factors that influenced it helped predict the potential of forests as carbon sinks. However, the contribution ratio of soil microbial necromass carbon to organic carbon under artificial afforestation in karst stony desertification areas and its variation with forest age were still unclear. To address this gap, this study focused on *Dalbergia odorifera* plantations with different planting ages (4, 11, and 18 years) in Pingguo City, Guangxi, as well as nearby naturally restored secondary forests. We utilized advanced biomarker techniques to accurately quantify the contribution ratio of microbial necromass carbon to organic carbon across these different forest types. Furthermore, we employed high-throughput sequencing methods to reveal the diversity of arbuscular mycorrhizal fungi (AMF), assess the complexity of their co-occurrence networks, and analyze the processes of community assembly. Building on these findings, we then explored the relationship between the characteristics of AMF communities and the contribution ratio of microbial necromass carbon. The results showed that in *Dalbergia odorifera* plantations, the microbial necromass carbon stock in the soil of the 18-year-old forest was lower than that in the 4-year and 11-year stands. With increasing forest age, the soil carbon (C): nitrogen (N): phosphorus (P) ratio and the complexity of AMF networks gradually increased, while the contribution ratio of microbial necromass carbon to organic carbon decreased, with the AMF community assembly process shifting from being dominated by stochastic processes to deterministic processes. The contribution ratio of microbial necromass carbon to organic carbon showed a significant negative correlation with C:N, C:P, N:P, and organic carbon stock ($P<0.05$). Structural equation modeling analysis suggested that forest age increased the soil C:N:P ratio, enhanced the complexity of AMF symbiotic networks, and shaped the deterministic assembly process of AMF communities. The complexity of AMF networks and the deterministic assembly process together diminished the relative contribution of microbial necromass carbon to the organic carbon pool. Through this study, we clarified the trends in microbial necromass carbon stocks and their contributions to the organic carbon pool during the artificial afforestation process in karst rocky desertified areas, revealing key driving mechanisms from the perspective of soil AMF community structure characteristics. Additionally, this research offered valuable scientific evidence and guidance for ecological restoration practices in karst rocky desertification areas.

# Nitrogen addition promotes soil microbial-derived carbon storage: A meta-analysis

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## ABSTRACT

The concept of soil microbial carbon pump highlights microbial necromass as a critical and persistent source of soil organic carbon (SOC). However, the response of soil microbial necromass carbon to nitrogen enrichment, particularly regarding the contributions of bacterial and fungal necromass to SOC, remains unclear. Here, a global meta-analysis with 791 paired observations from 56 studies was conducted to evaluate the influence of nitrogen addition on soil microbial necromass accumulation and its contribution to SOC storage. Nitrogen addition increased total microbial necromass carbon by 14.6%, with bacterial and fungal necromass carbon increasing by 17.7% and 13.7%, respectively. The extent of microbial necromass accumulation increased with nitrogen application rate and was concurrently modulated by soil properties, particularly total nitrogen and the soil carbon-to-nitrogen ratio. Nitrogen addition enhanced bacterial carbon pump efficacy (i.e. the proportion of bacterial necromass carbon in SOC), indicating improved carbon retention during bacterial metabolism. However, fungal necromass remained the dominant contributor to the increase in SOC after nitrogen addition, accounting for 18.9% of the SOC increment, compared with 6.5% from bacterial necromass. Overall, nitrogen addition stimulates microbial necromass formation, thereby enhancing SOC storage. Although bacterial carbon pump efficacy significantly increases owing to nitrogen addition, fungal necromass remains the dominant contributor to SOC accumulation. This study provides new insights into microbial-derived carbon storage after nitrogen enrichment.

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# Microbial growth rate is a stronger predictor of soil organic carbon than carbon use efficiency

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## ABSTRACT

The extent to which microbial processes control soil organic carbon (SOC) dynamics remains uncertain. Carbon use efficiency (CUE)—the fraction of assimilated carbon allocated to growth—has been used as a key parameter, but its relationship with SOC reflects carbon partitioning rather than the absolute magnitude of microbial fluxes. Microbial growth rate could provide a more mechanistic link to SOC accumulation, as it quantifies biomass production and reflects necromass formation. Here we combine a global $^{18}O$–$H_2O$ dataset (n = 268 paired observations) with outputs from four land surface models to test whether growth rate predicts SOC more strongly than CUE. In the incubation experiments, growth rates are more closely associated with SOC than CUE, although soil properties and climate explain equal or greater variance. Models reproduce the stronger role of growth rate over CUE but tend to underestimate the abiotic controls. The models also emphasize CUE as the main predictor of the SOC/NPP ratio, in contrast to observations, which indicates the soil's capacity to retain plant carbon inputs. Together, these findings identify microbial growth rate as a diagnostic that can help bridge models with empirical data and guide a more balanced representation of microbial and mineral controls in SOC projections.

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# Trade-off between Pore-Throat Structure and Mineral Composition In Modulating the Stability of Soil Organic Carbon

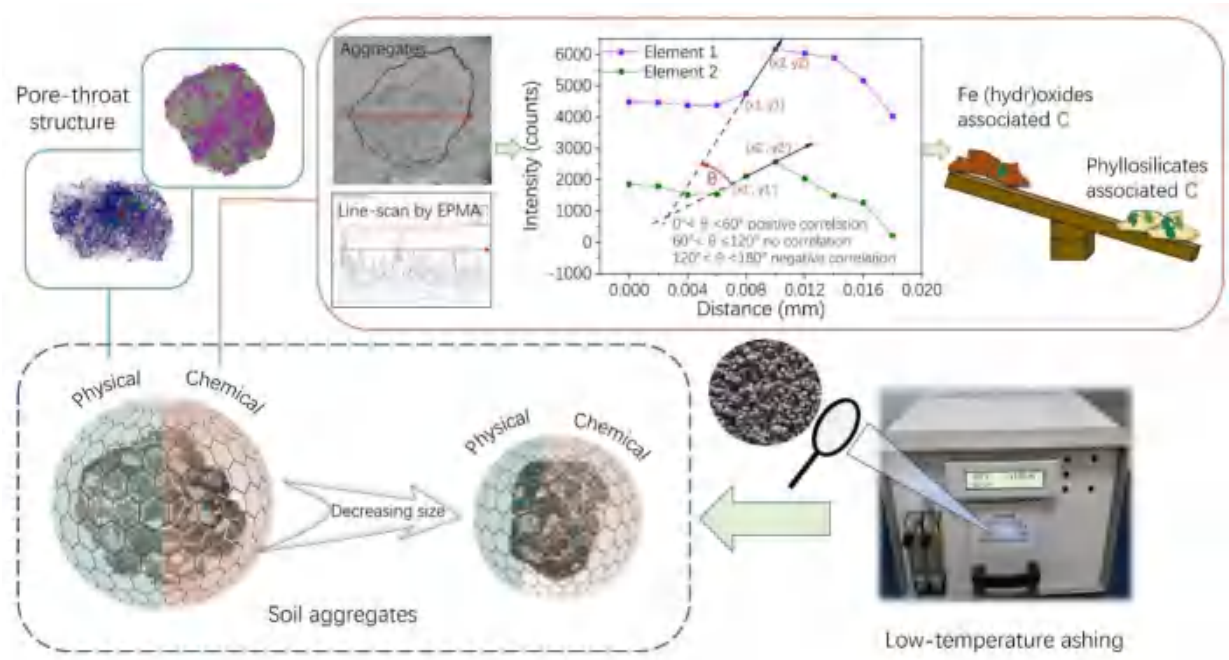
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## ABSTRACT

The preservation of soil organic carbon (OC) is an effective way to decelerate the emission of $CO_2$ emission. However, the coregulation of pore structure and mineral composition in OC stabilization remains elusive. We employed the in situ nondestructive oxidation of OC by low-temperature ashing (LTA) combined with near edge X-ray absorption fine structure (NEXAFS), high-resolution microtomography (μ-CT), field emission electron probe micro analysis (FE-EPMA) with C free embedding, and novel Cosine similarity measurement to investigate the C retention in different aggregate fractions of contrasting soils. Pore structure and minerals contributed equally (ca.50%) to OC accumulation in macroaggregates, while chemical protection played a leading roleinCretentionwith53.4%−59.2%of residual C associated with minerals in microaggregates. Phyllosilicates were discovered to be more prominent than Fe(hydr)oxidesinCstabilization.Theproportionofphyllosilicates-associated C (52.0%−61.9%) was higher than that bound with Fe(hydr)oxides (45.6%−55.3%) in all aggregate fractions tested. This study disentangled quantitatively for the first time a trade-off between physical and chemical protection of OC varying with aggregate size and the different contributions of minerals to OC preservation. Incorporating pore structure and mineral composition into C modeling would optimize the C models and improve the soil C content prediction.

## ABSTRACT graphic




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# Roots enhance the accrual of mineral-associated organic carbon via new carbon formation and microbial conversion of native soil carbon

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**ABSTRACT**

The stabilization of plant-derived carbon (C) and the modification of native soil organic matter (SOM) by fresh C input are key processes controlling soil C dynamics, yet the underlying mechanisms are not fully understood, particularly for the subsoil. Here, we conducted a two-year field incubation of $^{13}$C-labelled *Lolium perenne* roots in three grasslands (one alpine and two temperate), to study the incorporation of root-derived C into different SOM fractions and its effect on native SOM dynamics in top- (0–10 cm) versus subsoils (30−40 cm). After two years, the subsoil retained a higher proportion of the initial root C input (19.0 ± 0.8%) than did the topsoil (11.0 ± 1.7%), of which a greater fraction directly sorbed to the mineral-associated organic matter (MAOM) without prior microbial processing. The formation of root-derived MAOM was independent of the decomposition of root-derived light fraction (LF) and particulate organic matter (POM). In contrast, root inputs stimulated the microbial conversion of native POM and LF, leading to their stabilization as microbial-derived MAOM. Our results highlight the critical role of the subsoil in soil C sequestration and reveal that fresh C inputs enhance MAOM accrual via sorption of new C and microbial-mediated transformation of native soil C.

**Keywords:** Root decomposition, Carbon formation efficiency, Stable 13C-isotope, Biomarker, Microbial transformation, Grassland

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# Organic acid-mediated destabilization overrides warming effect on soil carbon mineralization

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## ABSTRACT

Soil organic carbon (SOC) mineralization is a key driver of the climate-carbon feedback. Enhanced microbial activity is considered to be the primary cause of SOC loss under warming. However, microbial trait changes often cannot fully explain SOC responses. Warming-enhanced root exudation of organic acids may destabilize mineral-associated organic carbon (MAOC) and promote SOC mineralization. However, this process remains poorly constrained both empirically and in Earth system models, impeding accurate predictions of soil carbon dynamics under climate change. To address the above gaps, here we integrate global data synthesis (8,846 observations from 112 studies) with laboratory quantification of organic acid-induced destabilization across diverse soils. We show that unlike carbohydrates that stimulate microbial growth, organic acids greatly accelerate SOC mineralization by increasing native carbon availability without enhancing microbial biomass or enzyme activity. By further quantitatively incorporating this abiotic pathway into the Millennial model, we find that organic acid-induced destabilization contributes 9% ± 1% (mean ± standard deviation) of SOC mineralization, surpassing direct warming effects by 25%–44% in climate projections (SSP1-2.6 and SSP5-8.5 scenarios), particularly on MAOC mineralization (by 81%–110%). Our study provides the first direct quantification of MAOC destabilization by root-exuded organic acids and shows its strong contribution to SOC loss across diverse soils in both laboratory observations and process-based models. Neglecting this pathway leads to an underestimation of SOC vulnerability, particularly for the slow-cycling MAOC pool. Laboratory experiments that exclude plant–soil interactions may also underestimate SOC loss by failing to capture root-induced destabilization.

**Keywords:** Root exudates, Organic acids, Carbon destabilization, Millennial model, Mineral-associated organic matter, Soil organic matter

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# Multi-element evidence that soil organic matter persistence is not attributed to selective preservation or loss but an ecosystem property

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**ABSTRACT**

Soil organic matter (SOM) persistence played a central role in global carbon (C) cycle and soil productivity, but the mechanisms underlying SOM stability remain unclear. We revisited the emerging views about SOM persistence by combining a space-for-time substitution study with physical and density fractionation of SOM, wet-chemical extractions and non-destructive near edge X-ray absorption fine structure (NEXAFS) spectroscopy to characterise SOC functional groups and S chemical speciation. Soil samples were collected at three depths (0-10, 10-20 and 20-30 cm) from the forest, and adjoining cropping and grazing lands at the Brigalow Catchment Study (BCS) in subtropical Australia. Bulk soil was then fractionated into free particulate organic matter (fPOM), occluded POM (oPOM), fine mineral fraction (f-MF) and coarse MF (c-MF). We found that cropping and grazing markedly decreased SOC and S concentrations in soil from the forest (especially at 0-10 cm), with the decrease being much more prominent for fPOM compared to oPOM or f-MF. Furthermore, even though the SOC functional group composition and organic S speciation differed significantly between the various soil fractions, they remained comparatively constant following land use change. Thus, despite losing up to 43% of the SOC, our observation that the speciation of both organic C and organic S did not change suggests that this loss of SOM was not associated with selective preservation (or selective loss) of particular forms of SOM, but rather highlighting the likely important role of physicochemical protection. Interestingly, cropping and grazing greatly simplified the interconnectivity networks of SOC functional groups and S chemical species for the forest soil, potentially indicating that SOM persistence was profoundly influenced by the interactions of multielements. We also observed that C-bonded S was positively correlated with the Shannon diversity index and aromaticity of SOC, suggesting an intrinsic linkage between SOC cycling and S. Our findings support Schmidt et al. (2011) that SOM persistence is an ecosystem property and not a molecular property, and extend their conclusions through multi-element analysis of SOM composition and speciation.

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# Root exudates drive grass-specific carbon sequestration through microbial networks in citrus orchards

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**ABSTRACT**

Grass cover profoundly modifies rhizosphere carbon cycling, yet the mechanistic links between root exudate chemistry and soil carbon stabilization remain elusive. A field experiment was conducted in a citrus orchard (Sichuan Province, China) with purple soil (pH 4.55) to investigate how root exudates modulate microbial networks and carbon fractions, using four grass species—natural grass (*Gnaphalium affine*), *Lolium multiflorum*, *Trifolium repens*, and *Vicia villosa*—and clean tillage as the control. Among all treatments, the leguminous *Vicia villosa* exhibited the most pronounced effect on carbon sequestration: compared with clean tillage, it markedly increased soil organic carbon (SOC), particulate organic carbon (POC), and mineral-associated organic carbon (MAOC) by 6.92, 4.37, and 2.55 g $kg^{-1}$, respectively, and elevated the POC/SOC ratio by 25%. Grass-specific root exudates were dominated by lipids (27.7%) and organic acids (19.2%), while *Vicia villosa* uniquely released nitrogen-rich metabolites such as lysine–leucine and adenine. These metabolites enriched keystone bacterial taxa (e.g., *Bacilli*, *Acidimicrobiia*), enhanced bacterial network connectivity (with higher positive edge proportions and natural connectivity), and promoted metabolic cross-feeding and organo-mineral complex formation. Partial least squares structural equation modelling (PLS-SEM) confirmed that root exudates strongly regulated bacterial networks (path coefficient = 0.78, $p < 0.001$), which directly increased POC (path coefficient = 0.46) and MAOC (path coefficient = 0.55); in contrast, fungal networks exerted negligible effects on both carbon fractions. Our findings elucidate a root exudate–bacterium co-regulation mechanism underlying soil carbon stabilization and provide a mechanistic basis for designing carbon-smart orchard management strategies through legume-based grass cover.

**Keywords:** Grass cover; Root exudates; Microbial networks; Carbon stabilization; Citrus orchard

**Acknowledgments**

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# Insights from soil-aggregate microbiome and in-field soil respiration for improved carbon sequestration assessment of land use practices

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**ABSTRACT**

Estimating aggregate-associated mineral-associated organic carbon (MAOC) and microbiome structure provides critical insights into soil organic matter (SOM) stabilization in biogenic aggregates, particularly in sandy soils lacking 2:1 clay minerals and carbonates. The accumulation or loss of MAOC, and thus the capacity for SOM stabilization depends on the balance between microbial catabolic mineralization and anabolic processes. By linking snapshot microbiome structure with in-field soil respiration measurements, we obtained a reliable indicator of a land use system's potential for SOC stabilization. This study tested the hypothesis that biogenic soil aggregation in sandy soils is highly responsive to management practices. We compared poorly managed intensively grazed lands (IGLs), with high grazing pressure and continuous nitrogen fertilization, to optimally managed IGLs featuring lower grazing pressure and legume integration. Weekly field-based $CO_2$ emission measurements over one year were paired with assessments of aggregate stability, MAOC, particulate organic carbon (POC), and microbial community structure, comparing long-term IGLs to a forestry site.

The results revealed that soil aggregation increased in heavily grazed systems, yet total MAOC levels were inversely affected. The highest MAOC was observed in optimally grazed IGLs, with small micro and clay-silt aggregates storing 45% and 41% of total MAOC, respectively, while large macro aggregates held the remainder. Although overall microbial diversity and structure did not vary significantly among aggregate fractions, aggregates with lower MAOC showed a higher abundance of copiotrophic microbes. In-field soil respiration data further indicated that systems with higher soil respiration tended to accumulate lower MAOC, even when exhibiting a higher aggregate stability index, whereas systems with lower soil respiration accumulated higher MAOC. These findings suggest that in sandy soils, MAOC formation is governed more by microbial community structure and activity, which are influenced by nutrient inputs from grazing than by the presence of biogenic aggregates alone.

**Key words:** MAOC in micropores, microbial community shift, r-strategist role, heterotrophic respiration

# Short-term effects of Amynthas earthworms on litter decomposition and $CO_2$ emissions in a temperate forest

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**ABSTRACT**

Earthworms are key decomposers in forest ecosystems influencing litter breakdown and nutrient cycling through their consumption of soil, microbes, and organic matter, as well as through bioturbation and cast production. This study investigated the short-term effects of *Amynthas* earthworms on $CO_2$ emissions in a *Quercus* spp. dominated mixed temperate forest over a 50-day period from September 9 to October 28, 2025. Eight cylindrical chambers (18L) with mesh bodies were embedded in the forest floor consisting of two treatments: control (soil + *Quercus acutissima* litter) (S, n=3) and earthworm-added (soil + *Q. acutissima* litter + earthworms) (SE, n=5) treatments. Soil $CO_2$ emissions were measured 16 times on days 1, 2, 3, 4, 6, 8, 10, 13, 15, 18, 21, 24, 31, 37, 43, and 50. *Amynthas* earthworms showed temporally variable effects on $CO_2$ emissions over the period. To examine temporal patterns, we divided the period into early (days 0-24) and late (days 25-50) phases based on observed shifts in $CO_2$ emissions. Earthworm effects were negligible during the early decomposition phase ($P = 0.375$) but became highly significant during the late phase ($P = 0.002$). Cumulative $CO_2$ emissions in SE reached $11.2 \pm 0.4$ g C $m^{-2}$ compared to $8.0 \pm 0.4$ g C $m^{-2}$ in S by day 50 representing a 39.5% increase. Both treatments exhibited an initial $CO_2$ emission peak during the first week following litter addition followed by a gradual decline after day 31. However, during the late phase, SE maintained relatively higher $CO_2$ emissions compared to S suggesting that earthworms sustained microbial decomposition activity after depletion of readily available substrates. These results indicate that earthworm effects on carbon mineralization are most pronounced during the late phase of litter decomposition with implications for organic matter turnover and nutrient availability though the underlying mechanisms should be further investigated.

**Acknowledgments**

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# Straw input altered the composition of aggregate-associated organic carbon in soils with different initial carbon status

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**A B S T R A C T**

Initial soil carbon (C) status affects microbial utilization for plant residue. Meanwhile, the retention of organic components from plant and microbial sources are also regulated by soil aggregates. Nevertheless, the information about how crop straw incorporation affects aggregates-associated organic C sources and composition is poorly understood, especially in soils with different initial soil C status. Here, the initial low and high C soils were incubated with or without the addition of maize straw for 360 days. We investigated the accumulation of lignin phenol and microbial necromass and the chemical composition of organic C within soil aggregates (macroaggregates, >0.25 mm; and microaggregates, < 0.25 mm) in initial low and high C soils following maize straw addition. Maize straw addition increased the organic C-normalized content of total lignin phenol within macroaggregates by 39% in initial low C soil, but decreased that content within both macroaggregates and microaggregates by 18% and 41% in initial high C soil, respectively. Independent of initial soil C status, maize straw addition increased the contributions of amino sugar and fungal necromass C to organic C within macroaggregates. Furthermore, maize straw addition increased the relative proportion of O-alkyl C in organic C within microaggregates in initial low and high C soils. Overall, the accumulation of plant lignin components was important for macroaggregate-associated organic C pool after adding maize straw to initial low C soil. Microbial necromass and labile organic components played divergent roles of in mediating aggregate-associated organic C in soils following maize straw addition.

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# Ferrihydrite-mediated carbon stabilization and plant responses in an alkaline soil

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**ABSTRACT**

Alkaline soils, which cover over 1.38 billion hectares globally, often constrain agricultural productivity due to their high pH and associated issues such as nutrient imbalances (e.g., reduced availability of P, Ca, and Mg), boron toxicity, poor soil structure, and limited root growth. While their low organic carbon (OC) content is a secondary outcome of these limitations, the role of reactive iron (Fe) minerals in stabilizing OC within such soils has been traditionally underestimated. However, recent evidence challenges this view, suggesting that Fe oxyhydroxides play a significant role in mineral-associated organic carbon (MAOC) stabilization in arid soils.

To address this knowledge gap, we conducted two experiments. The first investigated the effect of ferrihydrite (Fh) and a redox mediator (AQDS) on OC stabilization. We hypothesized that Fh would form Fe-bound OC complexes that protect OC from microbial degradation and AQDS would further reduce $Fe^{3+}$ to $Fe^{2+}$, therefore enhancing Fe-OC formation. In the second experiment, a subsequent 100-day pot experiment with wheat (*Triticum aestivum* L.) in alkaline soil was conducted, using Fh amendments (0.1% and 0.5% Fh). We traced the fate of carbon in the rhizosphere with increasing Fh amendments (0.1% and 0.5% w/w).

The results of the incubation experiment showed that the combined Fh and AQDS treatment enhanced Fe-OC complex formation while reducing basal soil respiration by 32% compared to the control. Synchrotron-based spectroscopy confirmed that carboxyl and phenolic functional groups contributed to the rapid adsorption of OC onto Fe surfaces, and therefore the stabilization of OC.

In the second experiment, the Fh 0.5% treatment significantly improved plant growth, increasing shoot and root biomass by over 40% by Week 13. Two $^{13}CO_2$ pulse-labelling campaigns were conducted at Weeks 7 and 13 to trace rhizodeposited-$^{13}C$. Through C source partitioning, Fh stimulated active C cycling, by increasing rhizodeposit-derived respiration and root respiration early in the growth cycle. We will further quantify the $^{13}C$ allocation into MAOC and particulate organic carbon pools and assess changes in water-stable aggregate stability. This work demonstrates that Fh amendments affect organo-mineral and biological processes in the rhizosphere to enhance C sequestration, highlighting a promising strategy to improve soil carbon stabilization and resilience in global dryland agriculture.

**Acknowledgments**

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# Long-term organic amendment in a maize cropping system enhanced $CO_2$ emissions via stimulation of oligotrophic microbial decomposition of chemically recalcitrant dissolved organic matter compounds

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## ABSTRACT

Agricultural fertilizer regimes can dictate soil's carbon storage capacity, but the mechanisms are complex and unclear. Long-term studies on dissolved organic matter (DOM) components and microbial decomposers are needed to improve soil carbon sequestration. Towards addressing these ends, Fourier Transform Ion Cyclotron Resonance Mass Spectrometry (FT-ICR-MS) combined with high-throughput sequencing could elucidate variations of DOM chemo-diversity, biodiversity, and their interactive effects on $CO_2$ emissions. A 29-year fertilized field experiment included four regimes (non-fertilization, CK; chemical fertilization, NPK; NPK with manure, NPKM; and NPK with stover return, NPKS). Results revealed organic amendments strongly increased $CO_2$ emissions by 19%–33% compared with NPK treatment. The relative abundance of recalcitrant DOM was depleted while the relative abundance of labile DOM components significantly increased in organic amendment treatments compared with the NPK treatment, as confirmed by decreases metrics of DOM chemical complexity, including SUVA254, Shannon index, and the nominal oxidation state of carbon. Organic amendments significantly increased the relative abundances of Acidobacteria, Chloroflexi, and Ascomycota compared with NPK treatment. Network analysis revealed that the organic fertilizer network had fewer DOM-microbial positive interactions compared with no-organic fertilizer networks, indicating a decreased specialization of DOM production. Conversely, higher DOM-microbial negative interactions indicated an increased specialization of DOM decomposition. These were attributed to an increase/decrease in the relative abundance of key microbes in the networks. Consequently, these findings revealed that the most of $CO_2$ in soils treated with organic amendments derived from recalcitrant components, which were decomposed by persistent DOM decomposers. This research highlights the significance of organic amendments responsive taxa in changes of DOM chemo-diversity and carbon loss.

# A repeat-pulse field labeling study to trace the fate of $^{13}C$ and $^{15}N$ labelled canola and durum crop residues in plant and soil organic matter on the Canadian Prairies

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## ABSTRACT

Soil organic carbon (SOC) plays a central role in maintaining soil health and fertility in agroecosystems, and its stability significantly influences the sustainability of agricultural production. The persistence of SOC depends on a number of factors, chief among them being the plant biomass C and nitrogen (N) inputs that are then stabilized within the soil. Producers on the Canadian prairies are moving towards more diversified cropping systems, which can increase ecosystem services and affect overall crop residue C and N inputs to soil, thereby impacting SOC status. There is a knowledge gap regarding the fate of C and N from crop residues in SOC, particularly for canola and durum in diversified cropping systems. We addressed this gap using an *in-situ* stable isotope ($^{13}C$ and $^{15}N$) labeling technique to label both above-and below-ground of durum and canola and swap between control (unenriched crop) and enriched crop above-ground residues in intensified and diversified cropping systems under field conditions. The study, conducted over three years (2023–2025) at the AAFC Swift Current Research and Development Centre in SK investigated three rotations: (1) conventional rotation system (Durum-Fallow-Durum-Malt barley); (2) a pulse-intensified system (Durum-Lentil-Durum-Chickpea); and (3) a multiple-commodity diversified system (Canola-Pea-Durum-Lentil). Results showed that crop above-ground production differed significantly among rotations but was unaffected by the repeat pulse field labeling. The concentrations (atom%) of $^{13}C$ and $^{15}N$ in straw, grain and root of labelled durum and canola were significantly greater than those in control treatments without isotope labelling. The averaged $^{13}C$ in soils with enriched plant root inputs at 0-7.5 and 7.5-15 cm were significantly greater than those in control treatments without enriched plant root inputs at time 0, 6 and 18 months crop above-ground residues returning to soil. This demonstrates that root C inputs contribute more to SOC than above-ground biomass C inputs due to greater root C decomposition. The $^{13}C$ and $^{15}N$ repeat-pulse field labeling is a powerful tool to trace above-and below-ground plant C and N allocation and estimate root C and N inputs to soil, shedding light on the fate of photosynthesized C inputs in SOC, therefore accurately estimate C footprint of diversified cropping system.

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We would like to thank the Agriculture and Agri-Food Canada (AAFC) and Western Grains Research Foundation (**WGRF**) for their funding and support.

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# Soil Carbon Dynamics and the Observer Effect

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**ABSTRACT**

To better predict soil C response to management and climate change, soil C scientists have striven to develop chemical and/or physical procedures to separate and quantity pools that cycle at largely differing rates. However, do these observational methods achieve the goal of probing the C dynamics of the *in situ* soil system? Here, soil is viewed as a complex, functioning, 3d system, with two domains of water and C flow that appear to function at differing rates, and which in turn control soil C response to perturbations. In contrast, all physical fractionation schemes are essentially post-mortem analyses of the soil system following an enormous observer-induced impact on the natural system, and these methods separate C fractions that are orthogonal to the natural functioning *in situ* system. The ever-growing databases of physical fractions and their chemistry reveal that they appear to identify the transformation of C from the plant to highly altered compounds, but that these physical fractions have only modest differences in their dynamics. A challenge for 21st century soil C science is to strategize ways of probing soil C dynamics of the *in situ* soil system while simultaneously reducing observer-induced artifacts to the resulting observations.

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# Rapid soil formation and carbon accumulation along a Little Ice Age soil chronosequence in southeast Alaska

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**ABSTRACT**

This study aims to assess the co-evolution of soil development and soil organic carbon (SOC) accumulation along a postglacial soil chronosequence in southeast Alaska. We hypothesize that in the early stages of soil development, a larger SOC pool is predominantly distributed in surficial soil horizons and gradually migrates to subsurface horizons. Seven moraines were dated using dendrochronology, yielding ages of 73, 82, 89, 128, 155, 207, and 247 years. SOC and pedogenic Fe oxyhydroxide values from mature Spodosols, sampled outside the chronosequence, were used as a References for the steady state of Spodosols in the region. From 73 to 128 years, soils were classified as Typic Cryorthents; by 155 years, as Spodic Dystrocryepts; and as Typic Haplocryods in the older moraines. A shift in SOC accumulation rates and depth distribution occurred once spodic properties developed. During the Entisol phase, most SOC stocks were concentrated in surficial horizons. After meeting spodic criteria, there was a shift toward subsurface mineral horizons, hosting over 50% of SOC stocks. This shift in SOC depth distribution was supported by a significant positive relationship between subsurface SOC stocks and age, but not with surficial SOC stocks. Similarly, surficial SOC accumulation rates were elevated during early pedogenesis (e.g., 0.26 Mg C $ha^{-1}$ $yr^{-1}$), while subsurface SOC accumulation was lower (0.05 Mg C $ha^{-1}$ $yr^{-1}$), increasing to 0.19 Mg C $ha^{-1}$ $yr^{-1}$ once spodic properties were met. A significant positive correlation between pedogenic Fe and age highlights the role of SOC in enhancing the weathering of Fe-bearing minerals. Our findings support the hypothesis that subsurface SOC stocks rapidly become dominant over time with Spodosol development. This study underscores the consequences of glacier retreat on a portion of the terrestrial ecosystem, with direct impacts on carbon and nutrient cycling.

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We acknowledge that the Herbert Glacier valley in Juneau, southeast Alaska is located on the unceded land of the Tlingit people. This research was funded by the Bates Summer Research Fellowship and the Hoffman Support Grant. We extend our gratitude to the Pacific Northwest Research Station – Juneau Forestry Sciences Laboratory for the field and lab support. We also thank the Upward Bound program and the Juneau Icefield Research Project (JIRP) for their fieldwork support in soil and tree core sampling. We also thank Philip Dostie from the Department of Earth and Climate Sciences (Bates College) for his assistance in the laboratory.

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# Distribution Characteristics of Soil Labile Organic Carbon Fractions in Coastal Paddy Profiles with Different Fertility Levels

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## ABSTRACT

Changes of soil labile organic carbon (LOC) and soil organic carbon(SOC) sequestration plays an important role in regulating rice yield and terrestrial carbon cycling. The changes in soil fertility level may impact the accumulation characteristics of LOC fractions in paddy profiles. However, the characteristics of LOC change in paddy profiles under different soil fertility levels remain unclear. In the study, Ten soil samples were collected in coastal saline paddy profiles at 0-20, 20-30, 30-40 and 40-50 cm depths in Panjin, Liaoning Province, China, for high-fertility (more than 9 tons yield per hectare) and low-fertility (less than 6 tons yield per hectare) soil, respectively. This study compared the changes in SOC and LOC fractions across different soil fertility-levels and explored interrelationships of these soil factors. The results showed that the SOC and most LOC fractions content in both high and low fertility soils decreased significantly as soil depth increasing, with notable differences between the 0-20cm depths layer and other deeper layers, except for those of dissolved organic carbon(DOC). The easily oxidizable carbon (EOC) with high-fertility paddy was higher than that of low fertility paddy in each soil layer. The microbial biomass and carbon (MBC) content in high and low fertility paddy both dramatically reduced with the increase of layer depth ($p=0.001<0.05$), and there was no significant difference between 30-40 cm and 40-50 cm soil layers. The DOC content was not related to the changes of soil depth.

Correlation analysis indicated that SOC content exhibited highly significant positive correlations with EOC content in each layer and MBC content in the 0-20 cm layer ($P < 0.01$), but showed no correlation with DOC content because of its most active component in the LOC fractions (Huang W.Z., 1998).

In summary, The EOC and MBC in LOC fractions influences SOC storage through soil fertility levels, which in turn alters the distribution of SOC and LOC fractions at the soil layer scale. This study highlights the important role of soil fertility levels modifications in paddy carbon storage and cycling processes, providing valuable insights for coastal saline paddy restoration and management.

**Key words: coastal saline paddy；active soil organic carbon components；profile distribution**

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# Toward a standardized and ecologically relevant framework for soil organic matter physical fractionation

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## ABSTRACT

Soil physical fractionation serves as a fundamental tool in characterizing the structure and stability of soil organic carbon pools. However, the absence of standardized critical parameters, particularly regarding flotation density and dispersion energy input, has significantly hindered cross-study comparability. To address this methodological gap, we systematically evaluated the separation efficiency of different combinations of flotation density (1.6 vs. 1.85 g $cm^{-3}$) and dispersion energy (100–500 J $mL^{-1}$) on forest, grassland, and wetland soils, respectively. By integrating a complementary long-term nitrogen (N) addition experiment, we independently validated the ecological relevance of the fractionation schemes. This effort aimed to establish a standardized protocol that is both universally applicable and ecologically meaningful. Our results revealed that the recovery of light particulate organic matter (LPOM) was primarily controlled by flotation density, whereas heavy particulate organic matter (HPOM) was highly sensitive to dispersion energy. The mineral-associated organic matter (MAOM) fraction was governed by both parameters. Importantly, the responses of all these fractions to parameter changes exhibited ecosystem dependence. Based on these findings, we propose optimized parameter sets tailored to different ecosystems. For instance, a combination of low density (1.6 g $cm^{-3}$) and low-to-medium dispersion energy (200–300 J $mL^{-1}$) is recommended for forest and grassland systems, while the optimal density for wetland systems requires selection based on the specific fractionation objectives. Further validation via the long-term N addition experiment demonstrated that this optimized scheme successfully captured predictable response patterns of each SOM fraction to N enrichment, confirming its strong ecological explanatory power. The standardized fractionation protocol established in this study offers a robust methodological framework for the accurate assessment and prediction of soil carbon cycling responses to global change across diverse ecosystems.

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# Straw-Induced Carbon Dynamics in Saline Soils: Insights from $CO_2$ Emissions to Soil Organic Carbon Sequestration

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**ABSTRACT**

Straw application is an efficient strategy for reclaiming saline soils and enhancing soil organic carbon (SOC) sequestration. However, the influence of salinity on straw-derived carbon turnover remains unclear, thereby limiting our ability to accurately assess the carbon sequestration in saline agroecosystems. A soil incubation experiment was thus conducted using $^{13}C$-labeled maize straw. Four salinity levels were arranged: low salinity (LS, 3.0 g $kg^{-1}$), moderate salinity (MS, 5.0 g $kg^{-1}$), high salinity (HS, 10.0 g $kg^{-1}$), and severe salinity (SS, 15.0 g $kg^{-1}$). During soil incubation, straw-derived carbon mineralization to $CO_2$ and conversion into different SOC fractions: free particulate organic carbon (fPOC), occluded particulate organic carbon (oPOC), and mineral-associated organic carbon (MAOC) were investigated. Compared with the LS treatment, salinity significantly inhibited the cumulative $CO_2$ emissions and the amount of mineralized straw by 3.6%-26.8% and 2.7%-15.6% respectively. Meanwhile, the priming effect decreased by 3.4%-26.5% and its duration obviously increased. With increasing salinity, straw conversion into fPOC and MAOC fractions boosted by 21.7%-72.1% and 0.6%-29.5% compared to the LS treatment. The activities of soil dehydrogenase, cellulase, and β-glucosidase were significantly inhibited under high salinity conditions. Correlation analysis and structural equation modeling confirmed the decrease in straw conversion into SOC pools was mainly ascribed to enzymatic activity reduction (path coefficient = -0.844, $P<0.01$). In a word, soil salinization significantly inhibited straw mineralization and conversion into oPOC and MAOC fraction, while increased straw conversion into fPOC fraction. The findings provide insights into SOC dynamics under different saline conditions, which could help us assess carbon sequestration potential and improve saline soil ameliorating efficiency through straw application.

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# Organic materials combined with microbial inoculants suppress priming effect and enhance SOC sequestration in sandy soil

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**ABSTRACT**

Soil organic carbon (SOC) sequestration plays a vital role in enhancing soil fertility and mitigating climate change. The application of organic materials, particularly straw return, has been a widespread practice to enhance SOC stocks. However, the sequestration potential of straw carbon remains suboptimal. It is generally agreed that microbial inoculants application is capable to facilitate decomposition of organic materials and soil nutrient release, yet the mechanisms by which the co-application of microbial inoculants and organic materials enhance SOC sequestration, especially in coarse-textured soils, remain inadequately understood.

We conducted a 90-day incubation experiment employing $^{13}$C-labelled maize straw and microbial inoculants in two contrasting soils: a fine-textured clay loam and a coarse-textured sandy soil.

Our results indicate that the co-application of microbial inoculants and straw significantly enhanced SOC sequestration. Specifically:

1. Compared to straw addition alone, microbial inoculants accelerated straw mineralization and suppressed PE by 8.98% in clay loam and 43.98% in sandy soil. This PE suppression was driven by alleviated microbial nutrient limitation and shifted the microbial community (lower $^{13}$C incorporation into the PLFAs of gram-positive bacteria vs. gram-negative bacteria). Microbial inoculants combined with straw further increased net SOC gain (clay loam soil: +6.7%, sandy soil: +619%) relative to straw alone. The superior SOC gain in sandy soil was attributed to its heightened responsiveness to microbial inoculants, leading to a greater increase in microbial carbon use efficiency (CUE) and $^{13}$C incorporation into phospholipid fatty acids ($^{13}$C-PLFA).

2. The combination of microbial inoculants and straw significantly increased SOC content in two soils. Specifically, compared with straw addition alone, straw combined with microbial inoculants boosted microbial necromass carbon (MNC) accumulation by 12.6% in clay loam and 28.6% in sandy soil, respectively. Although the contribution of MNC to SOC in sandy soil was lower than that in clay loam soil, the contribution of plant-derived C to SOC in sandy soil reached 40% (compared to less than 23% in clay loam soil). This suggested that in soils with lower clay content, plant-derived C is more readily preserved, whereas the MNC accumulation is comparatively less efficient. Additionally, the pathways of SOC stabilization were soil texture-dependent: in the clay loam soil, the increased MNC was strongly associated with mineral-associated organic carbon (MAOC) formation, while in the sandy soil, it was primarily stabilized within particulate organic carbon (POC) due to the scarcity of reactive mineral surfaces.

This study revealed that microbial inoculants with organic materials optimize SOC sequestration by suppressing PE and promoting MNC, but long-term SOC stabilization is contingent on soil texture. Overall, our findings offer critical insights and practical approaches for sustainable agricultural management of sandy soils.

**Keywords:** Microbial inoculants; Sandy soil; Priming effect; Microbial necromass; Particulate organic carbon (POC); Mineral-associated organic carbon (MAOC)

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# Reframing Manure Amendments and Nitrogen Inputs as Co-Determinants of Persistent Soil Organic Carbon in Semi-Arid Agroecosystems

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**ABSTRACT**

Achieving durable stabilization of soil organic carbon (SOC) remains a major challenge in dryland agroecosystems where substrate inputs, nutrient stoichiometry, and mineral–microbial interactions jointly constrain carbon persistence. Using a 20-year manure and nitrogen (N) fertilization experiment on the semi-humid Loess Plateau, integrated with microbial trait measurements, necromass biomarkers, lignin phenol profiling, extracellular enzyme stoichiometry, and aggregate–mineral fractionation, we establish a unified framework describing how multiple controls shape persistent SOC pools.

We first demonstrate that manure inputs, despite increasing total SOC, can lower SOC stability. High-C/N manure imposed chronic microbial N limitation, promoted resource-acquisition strategies, stimulated N-acquiring enzymes, and reduced microbial carbon use efficiency. These responses accelerated the decomposition of both labile substrates and microbial-derived compounds, weakened necromass stabilization, and diminished mineral-associated organic carbon (MAOC) formation.

Manure–N co-application fundamentally altered these pathways. Moderate N rates alleviated N limitation, suppressed N-degrading enzymes, improved microbial metabolic efficiency, and favored growth-yield strategies. Enhanced biomass turnover increased necromass production and promoted its incorporation into MAOC, and strengthened mineral-associated protection through elevated Fe/Al oxides and exchangeable Ca.

The optimal stabilization occurred under moderate manure with moderate N input, whereas high N addition diminished stability under high manure supply, highlighting a nonlinear nutrient–carbon interaction previously overlooked in SOC stabilization frameworks.

Aggregate-mediated protection displayed a threshold response. Combined manure and N inputs increased microaggregate formation and mineral–organic associations via elevated extracellular polymeric substances and glomalin-related proteins, whereas excessive N reduced these binding agents and decoupled physical structure from carbon protection. Machine-learning results indicated that chemical protection exerted the strongest direct influence on SOC stability, with microbial efficiency and physical protection acting as synergistic regulators.

Overall, this work integrates nutrient stoichiometry, microbial strategies, necromass dynamics, and mineral–aggregate interactions into a coherent explanation of SOC persistence. The findings refine current understanding of manure and N management and support strategies aimed at enhancing long-term carbon retention under climate-smart agriculture.

**Keywords:** Dryland agroecosystem; Organic and inorganic fertilizer; Nutrient stoichiometry; Microbial carbon use efficiency; Soil organic carbon stability

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# Molecular signatures of soil organic matter diverge under long-term manure versus straw amendments in agricultural Mollisols

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## ABSTRACT

Since large-scale agricultural reclamation, the quantity and quality of soil organic matter (SOM) in Mollisols have dramatically declined, leading to reduced stability. The application of organic amendments promotes soil aggregate formation and enhances carbon sequestration potential. However, how the molecular characterizations of SOM respond to organic material application across different years remains unclear. This research investigated farmland Mollisols subjected to different organic amendment practices (organic manure and straw return), analyzing the molecular structure, composition, and sources of SOM in topsoil (0-20 cm) using nuclear magnetic resonance (NMR), molecular mixing models, Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS), and biomarker techniques.

Results indicated that, for SOM in bulk soils, compared to chemical fertilizer application, short-term (6 years) straw return significantly reduced the SOM degradation degree by 14.7%, attributable to a 70.7% decrease in char and a 12.9% increase in carbohydrates. Relative to initial year, long-term (12 years) organic manure application significantly reduced soil hydrophobicity by 5.8% through accumulating lignin (+7.3%) and depleting carbohydrates (-7.8%). In contrast, straw return significantly and persistently reduced the soil lipidization degree by 13.5%-15.3% through increasing char and carbohydrates (by 39.5-187.7%) and decreasing lignin (by 12.4-13.6%).

For soil dissolved organic matter (DOM), compared to chemical fertilizer application, short-term organic manure application significantly reduced the DOM degradation degree by 10.2%, associated with a 22.8% decrease in lipid-like compounds. In contrast, long-term straw return significantly increased the DOM degradation degree by 17.1%, due to substantial increases in lipid-, carbohydrate-like compounds, and unsaturated hydrocarbon content (+1.1-3.4 fold) and a 41.3% decrease in lignin-like compounds. Relative to the initial year, organic manure led to the depletion of protein-like compounds and unsaturated hydrocarbons, whereas straw return resulted in dramatic enrichment of lipid-, protein-like compounds, and unsaturated hydrocarbons, alongside sharp decreases in lignin- and tannin-like compounds.

Regarding organic matter sources, compared to chemical fertilizer application, organic manure application consistently increased the content of three lignin phenol monomers and total lignin phenols (by 70.2-532.5%), significantly elevating their proportion in SOM (by 59.4-76.6%). Simultaneously, it markedly altered the composition of microbially derived carbon: short-term application reduced the content of microbial residue carbon such as amino sugars, while long-term application increased the fungal-to-bacterial residue carbon ratio by 40.7% and consistently decreased the proportion of amino sugars. In contrast, straw return primarily influenced organic matter sources by altering lignin phenol monomer ratios and reducing the acid-to-aldehyde ratio of vanillyl phenols by 11.5%, while consistently decreasing the content of muramic acid and galactosamine by 20.2-31.8%.

In conclusion, this study demonstrates that long-term organic fertilization drives the molecular composition of SOM from "microbial-derived dominant" to "plant-derived dominant." Organic manure tends to accumulate recalcitrant plant-derived components and shifts the microbial community toward a fungal-dominated pathway, favoring long-term SOM stability. Conversely, straw return strongly stimulates a bacterial-dominated microbial cycle, enhancing DOM activity and accelerating the chemical transformation of SOM. These findings provide important theoretical insights into the microscopic mechanisms governing soil carbon sequestration and turnover under different organic management strategies.

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# Controls on the mineralization and stabilization of exogenous organic matter in volcanic soils

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## ABSTRACT

Soil C sequestration is determined by the balance between microbial mineralization and stabilization of exogenous organic matter (OM) inputs. We investigated the factors regulating the mineralization and stabilization of residue-derived C in OM fractions across soils differing in native organic matter content and mineralogical properties.

We used topsoil (0–15 cm) and subsoil (20–40 cm) from 8 sites along an elevation gradient of the Sierra Nevada in California. The soils, developed on andesitic lahar deposits, exhibited a wide range of soil organic C (SOC) (11–116 g C $kg^{-1}$) and oxalate-extractable Al/Fe ($Al_o$ + $Fe_o$) (10–127 cmol $kg^{-1}$). The soils were incubated with $^{13}C$-labeled plant material (8.4 mg per 20 g soil, equivalent to about 1 Mg OM $ha^{-1}$) at 25°C for 343 days. We measured the amounts of C and the $^{13}C$ ratio in $CO_2$ released during incubation, and in OM fractions (particulate OM, POM; mineral-associated OM, MAOM) and whole soil on days 28, 175, and 343. Spearman partial correlation analysis was used to test the effects of soil properties on the mineralization of added plant material and its stabilization in OM fractions.

The added plant material was predominantly mineralized within the first 28 days, accounting for more than 50% of the total mineralization. During this initial phase, SOC was positively correlated with plant-derived C in POM ($r$ = 0.75**) after controlling for $Al_o$ + $Fe_o$. $Al_o$ + $Fe_o$ generally showed negative correlations with the decomposition of the added plant material and positive correlations with remaining plant-derived C. Specifically, controlling for SOC, $Al_o$ + $Fe_o$ was negatively correlated with the mineralized plant material on days 28 ($r$ = –0.79***), 175 ($r$ = –0.66**), and 343 ($r$ = –0.71**), and positively correlated with the remaining plant-derived C in whole soil ($r$ = 0.78***). Furthermore, $Al_o$ + $Fe_o$ correlated positively with plant-derived C in MAOM on days 175 ($r$ = 0.70**) and 343 ($r$ = 0.53*) and with plant-derived C in POM on day 343 ($r$ = 0.58*) after controlling for SOC. In contrast, SOC showed positive correlations with mineralization and negative correlations with stabilization. Controlling for $Al_o$ + $Fe_o$, SOC was positively correlated with the mineralized plant material on days 28 ($r$ = 0.62*), 175 ($r$ = 0.74**), and 343 ($r$ = 0.79***) and negatively correlated with the remaining plant-derived C in whole soil ($r$ = –0.55*). SOC also showed negative correlations with plant-derived C in MAOM on days 175 ($r$ = –0.81***) and 343 ($r$ = –0.69**) after controlling for $Al_o$ + $Fe_o$.

In summary, at the early stage of incubation (around one month), soils with high SOC-accumulated exogenous OM in POM, which was subsequently decomposed. Our long-term incubation demonstrated that high SOC limited the incorporation of exogenous OM into MAOM and enhanced its mineralization. Conversely, $Al_o$ + $Fe_o$ suppressed the mineralization of exogenous OM and promoted its stabilization within both MAOM and POM.

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# Amplifying the soil mineral pump for carbon sequestration

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**ABSTRACT**

Effective carbon sequestration strategies are pivotal in mitigating climate change, while current approaches often overlook the critical role of soil minerals-the backbone of soils, in stabilizing organic carbon. Our study introduces a comprehensive framework to quantify the soil "Mineral Carbon Pump" (MnCP) [1], a previously unquantified mechanism by which soil minerals facilitate organic carbon stabilization. We first utilized data from 152 standardized pairs of soil organic carbon (SOC) and mineral-associated organic carbon (MAOC) collected from 15 globally distributed sites. These sites encompass diverse soil chronosequences, depth profiles, and land management practices. This was complemented by an analysis of 2,708 MAOC measurements across zones grouped by high or low mineral reactivity. Our findings demonstrate that the MnCP contributes between 19% and 230% to SOC sequestration. Soils with high-reactivity minerals exhibit a carbon sequestration potential of 70~85 g C $kg^{-1}$ soil, which is more than 1.6 times that of soils with low-reactivity minerals. This enhanced potential is equivalent to approximately 32~48 times the carbon dioxide emissions from anthropogenic activities in 2023. This study provides novel mechanistic understanding of the role of minerals in the soil carbon sink and has implications for the development of mineral-informed strategies for enhancing soil carbon sequestration.

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# Straw incorporation stimulated the intercropping effect to enhance soil carbon sequestration

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**ABSTRACT**

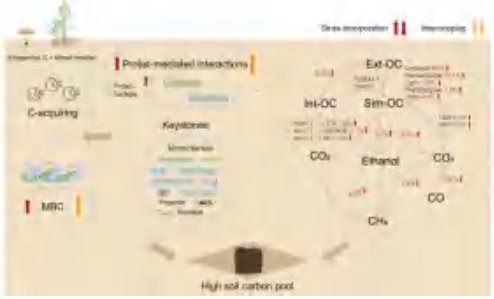
*Background and aims* The soil carbon pool, being the largest and most active carbon pool in terrestrial ecosystems, stores approximately 2000 Pg of carbon in the form of soil organic carbon (SOC). The sequestration of soil organic carbon is recognized as a powerful tool to mitigate climate warming, improve the quality of cultivated land soil, and achieve food security. Intercropping has been shown to significantly increase SOC content; however, the SOC sequestration process in such systems is often slow. Integrating straw incorporation offers a synergistic approach to enhance SOC more effectively by increasing exogenous carbon inputs. Yet, the underlying mechanisms by which intercropping combined with straw incorporation promotes SOC, particularly through microbial and micro-food web pathways, remain inadequately understood.

*Methods* Based on a long-term field experiment initiated in 2012 in Zhangye City, Gansu Province, we conducted a two-factor randomized block design with four replicates. The main-plot factors were different management practices, including nitrogen and phosphorus fertilizer application alone (NP), nitrogen and phosphorus fertilizer combined with straw incorporation (NP+ST). The sub-plot factors were different cropping systems, including pea monoculture, maize monoculture, and pea/maize intercropping. Bulk soil samples were collected during the bloom stage of peas. We integrated soil carbon-related indicators, amplicon and metagenomic sequencing data to explore how intercropping combined with straw incorporation enhances soil carbon sequestration by regulating soil food web and its functions.

*Results* Compared with monoculture, intercropping significantly increased SOC and soil mineral-associated organic carbon (MAOC) contents by 3.7% and 4.8%, respectively. Relative to the NP treatment, NP+ST significantly increased SOC and MAOC contents by 18.6% and 19.5%, respectively, and also enhanced soil particulate organic carbon (POC) and dissolved organic carbon (DOC) contents. Intercropping significantly increased soil microbial carbon (MBC) content and C-acquiring enzyme activity under NP+ST but not under NP treatment; enzyme activity was positively correlated with MBC content. Furthermore, random forest modeling identified MAOC and MBC as key predictors of SOC content.

Network analysis showed that intercropping enhanced cross-trophic interactions compared with monoculture. Under NP+ST treatment, intercropping significantly increased protist-mediated interactions and exhibited a greater number of keystones. These keystones were significantly positively correlated with soil carbon, Cercozoa and Ciliophora played dominant roles. Additionally, NP+ST increased the abundance of carbon fixation modules compared with NP treatment. Under NP+ST treatment, intercropping enriched more carbon fixation genes, among which *KorA*, *accC*, and *accD* were significantly positively correlated with soil carbon. Straw incorporation also significantly increased the abundance of plant-derived carbon degradation genes (cellulose and hemicellulose). Under NP+ST treatment, intercropping enriched hemicellulose degradation gene was significantly positively correlated with soil carbon. The abundance of key genes were significantly positively correlated with keystones.

*Conclusion* Straw incorporation can stimulate the intercropping effect and improve soil carbon sequestration by modulating potential keystones with carbon fixation and plant-derived carbon degradation functions. Our study provides theoretical support for enhancing the soil carbon pool by intercropping integrated with suitable conservation tillage practices.



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# The Long-Term Impact of Excess Phosphorus Saturation on Soil Organic Carbon Sequestration in Agricultural Soils

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## ABSTRACT

Intensive agriculture has led to substantial phosphorus (P) accumulation in Flemish (Belgium) cropland soils, yet its impact on soil organic carbon (SOC) storage remains uncertain. We hypothesize that excess P reduces SOC storage through diminished rhizodeposition, enhanced mineralization and competition between phosphate and organic anions for mineral-binding sites.

To evaluate this hypothesis, the influence of the degree of phosphate saturation (DPS) on C-stability and long-term SOC storage was assessed after approximately 30 years. The study focused on sandy, acidic agricultural soils in Flanders, where pedogenic Fe and Al (oxy)(hydr)oxides are the main sorbents for SOC and orthophosphate. A historical dataset of over 3,000 Flemish sandy agricultural soils, sampled in the 1990s, served as the basis for this study. A total of 83 fields were selected to represent a DPS gradient while maintaining comparable pH, clay content and sorption capacity. Cropping history of these fields included maize for at least 16 years. The soils on the selected fields were resampled at 0-30, 30-60 and 60-90 cm. The DPS for the resampled soils was determined using ammonium-oxalate extractions[1]. Subsequently, C-content and $\delta^{13}C$ values were measured via EA-IRMS for both the resampled and historical soils, allowing the estimation of 'new' maize-derived C using a $^{13}C$ mass balance[2]. Maize-derived C conversion efficiency (Maize-C CE) was defined as the proportion of maize-derived carbon retained in soil relative to the total estimated maize-C input over the study period.

Average Maize-C CE values over the past 30 years were 9.09 ± 6.15%, 31.58 ± 24.45% and 11.57 ± 12 % for the 0–30, 30–60 and 60–90 cm layers, respectively, and were not significantly affected by DPS. Given the large variability, we will investigate whether other parameters better predict the Maize-C CE. To further investigate SOC-P competition for mineral-binding sites, analyses are ongoing on A-horizon soils. Particle-size fractionation isolates the mineral-associated organic matter (MAOM) fraction to assess the relationship between DPS and C storage within this pool. Hydroxylamine extractions quantify C bound to Fe and Al (oxy)(hydr)oxides, providing insight into SOC-P interactions at elevated DPS. Furthermore, incubation experiments will be performed to assess the stability of maize-derived C, while batch-sorption experiments will test whether DPS influences the sorption capacity for different organic molecules.

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# Global warming and soil management impact on organic carbon stocks and dynamics in vineyard soils

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**ABSTRACT**

Climate change significantly affects soil organic carbon (SOC) stock and vulnerability, as well as microbial biodiversity, across different agro-ecosystems including vineyards. Due to the wide cultivation of wine grapes, the wine sector is now called upon to reconcile environmental protection, competitiveness, and resilience to global warming. The SUSTAIN project aims at determining the potential of vineyards, characterized by different pedoclimatic conditions and cultivars, on SOC accumulation in the context of climate change scenarios. A randomized block design, consisting of 3 blocks composed of 8 plots each, and 2 factors, i.e., land management practice (amendment with digestate, cover crop, bare soil) and climate manipulation (ambient temperature, warming), was set up in three study areas within the Veneto region (North of Italy). Open top chambers (OTC) were used to obtain a temperature increase of ~2 °C (SSP2-4.5). Soil samples have been collected at four times (after 0, 6, 12, and 18 months from the OTC placement) and at 3 depths (0-15, 15-30, and 30-45 cm) and characterized from the physical, chemical and microbiological point of view. From each sample, particulate and mineral-associated organic matter (POM and MAOM, respectively) were isolated and characterized by elemental and thermal analysis. DNA was extracted from topsoils, and metagenomic analyses and enzymatic assay were carried out.

The preliminary results indicated no significant differences in SOC stocks following short-term warming. On the opposite, a general and slight increase in SOC concentration already occurred after 6 months in plots with cover crops, where POM played a greater role in SOC accrual. Thermal analysis, which was used to evaluate SOC stability, underlined that, regardless of vineyard and agronomic management, POM is the more labile fraction, while MAOM showed an increase of stability with depth. On the other hand, no significant differences were observed among treatments and climate manipulations.

It is expected that results obtained at the end of experiment will help to better understand the SOC and microbial dynamics in vineyards as a function of future climate change scenarios. In addition, Life Cycle Assessment (ISO14040), which integrates experimental data and company inventories, will estimate the carbon footprint of the vineyards management. Ultimately, these outcomes will enable the identification of soil-management strategies that strengthen long-term carbon storage while substantially reducing the environmental impact of viticulture.

**Acknowledgments**

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# Soil pH modulates the global soil organic carbon stabilization

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**ABSTRACT**

Soils mineral-associated organic carbon (MAOC) constitutes over 50% of total soil organic carbon (SOC) and serves as a key determinant of its long-term stabilization. Although soil pH is recognized as a "master variable" in biogeochemical cycles, it remains unclear how soil pH influent MAOC and SOC stabilization at large spatial scales. To address this knowledge gap, we conducted a continental-scale survey in China and synthesized global observations from literature, totaling 1300 independent observations. By analyzing the relationships between SOC and MAOC across a pH gradient, along with the contributions of other environmental factors to MAOC variability, we found that while higher SOC content generally correlates positively with higher MAOC, this relationship is shaped by soil mineralogy, texture, and climatic conditions. Specifically, we identified two stabilization pathways governed by pH: in acidic soils (pH $\leq$ 5.5), Fe/Al (hydr)oxides explain most of the variation in MAOC content and MAOC/SOC ratio. Net primary productivity (NPP) and belowground NPP (BNPP) augment the particulate organic carbon (POC) pool, thereby diluting the MAOC fraction. In neutral-to-alkaline soils (pH > 6.5), however, clay content and mean annual temperature emerge as the primary regulators. This divergence challenges the universal applicability of clay-centric SOC models. Our findings provide a refinement information for biogeochemical models, urging the integration of pH-dependent metal oxide dynamics to improve predictions of SOC persistence under diverse future scenarios.

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# Effects of Long-term Chemical Fertilizer Reduction Combined with Bio-organic Fertilizer on Soil Organic Carbon Fractions and Aggregate Stability in Tobacco-planting Soil

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## ABSTRACT

Rational bio-organic fertilizer combination with chemical fertilizer has important advantages in enhancing chemical fertilizer use efficiency, inhibiting soil pathogen, improving soil fertility and crop yield and quality, is considered a key practice for improving soil health and crop green production. To investigate the effects of long-term chemical fertilizer reduction combined with bio-organic fertilizer on soil organic carbon fractions and soil aggregate stability in tobacco planting soil, a 12-year continuous field positioning experiment was conducted with five treatments: no fertilization control (CK), local conventional recommended fertilization (CF), 20% chemical fertilizer reduction (CR), 20% chemical fertilizer reduction combined with organic fertilizer (OF), and 20% chemical fertilizer reduction combined with bio-organic fertilizer (BOF). Soil samples were collected from the 0–20 cm layer to determine the contents of soil total organic carbon (SOC), dissolved organic carbon (DOC), labile organic carbon (LOC), and microbial biomass carbon (MBC).The soil organic carbon stock and sequestration, carbon pool management index (CPMI), and carbon pool sensitivity index (CSI) were analyzed The wet sieving method was employed to determine soil aggregate distribution, and the mean weight diameter (MWD), geometric mean diameter (GMD), fractal dimension (D), and R0.25 were calculated to characterize aggregate stability. The results showed that, compared with the local conventional recommended chemical fertilizer application (CF), 20% chemical fertilizer reduction combined with organic fertilizer (OF) and bio-organic fertilizer (BOF) increased the contents of SOC and all organic carbon fractions and sequestration . The BOF showed the most significant effects, with SOC, DOC, LOC, and MBC contents increased by 16.8%, 49.6%, 84.3%, and 53.4%, respectively, compared to the CF. Compared to the CF, the BOF increased the soil organic carbon stock and carbon sequestration amount by 32.2% and 55.7%, respectively. The CPMI increased by 86%, while the CSI was decreased by 10.3%. The BOF significantly increased the content of water-stable aggregates larger than 0.25 mm, with a 20% increase compared to the CF. The aggregate MWD, GMD, and R0.25 of the BOF were significantly higher than that of the CF by 26.1%, 11.1%, and 20.52%, respectively, while the fractal dimension (D) decreased by 2.5%. Correlation analysis revealed that, MWD, GMD, R0.25, and the content of water-stable aggregates were significantly positively correlated with the contents of DOC, LOC, and MBC, whereas the fractal dimension (D) was significantly negatively correlated with these indicators. In conclusion, long-term 20% chemical fertilizer reduction combined with bio-organic fertilizer can significantly increase the contents of various soil organic carbon fractions, effectively promote the formation of large soil aggregates, substantially enhance the water stability of soil aggregates, thereby synergistically enhance the soil carbon sequestration and improve the soil structural quality of tobacco-planting soil.

**Keywords:** Bio-organic fertilizer; Chemical fertilizer reductions; Soil Organic carbon fractions; Soil Aggregate stability, tobacco-planting soil

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# Effects of soil acidity on organic matter stabilization in Cryptomeria japonica and Chamaecyparis obtusa plantations

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**ABSTRACT**

Soil organic matter (SOM) represents the largest carbon (C) pool in terrestrial ecosystems, and mineral-associated organic matter (MAOM) is a key fraction that governs long-term C storage. Soil acidity, arising from both natural and anthropogenic processes, acts as a major regulator of SOM dynamics by altering microbial activity and organo-mineral interactions. Conventionally, high soil acidity has been thought to suppress litter decomposition, leading to the accumulation of less decomposed organic matter. However, our previous studies revealed that both particulate organic matter (POM) and MAOM exhibit higher degrees of decomposition in soils with low acid buffering capacity (low-ABC, pH < 5) than in soils with high-ABC (pH > 5) in plantations of two dominantly planted coniferous species in Japan, *Cryptomeria japonica* and *Chamaecyparis obtusa*. The low-ABC soils showed enhanced degradation of aromatic compounds during the transformation from POM to MAOM in soils of 0–10 cm depth at *C. japonica* stands and microbially metabolized MAOM with low stocks throughout the soil profile (0–40 cm depth) at *C. obtusa* stands. These findings suggest either high activity of specific microbes such as lignin-degrading fungi or long exposure to microbial decomposition in acidic soils. The latter may be attributed to the low efficiency of organic matter stabilization by soil minerals under acidic conditions, but the status of the organo-mineral association remains poorly investigated in the fields with different soil acidity. Thus, we aimed to clarify how soil acidity affects the stabilization of MAOM, as inferred from the ratios of C to extractable Al and Fe.

We collected soil samples from three depths (0–10, 10–20, and 20–40 cm) at 11 stands of *C. japonica* (7 stands for low-ABC soils and 6 stands for high-ABC soils) and 7 stands of *C. obtusa* (4 stands for low-ABC soils and 3 stands for high-ABC soils) in temperate central Japan. A total of 54 bulk soil samples were separated into three density fractions: a light fraction (LF, <1.8 g $cm^{-3}$) dominated by POM, a middle fraction (MF, 1.8–2.4 g $cm^{-3}$) rich in MAOM, and a heavy fraction (HF, >2.4 g $cm^{-3}$) primarily composed of minerals with minimal organic matter. For the MF and HF, Al and Fe associated with organic matter were sequentially extracted using pyrophosphate (PP, mainly organo-metal complexes), acid oxalate (OX, mainly short-range-order minerals), and dithionite-citrate (DC, mainly crystalline iron oxides) solutions. These reactive metal phases are known to exert strong control on SOM stability in acidic soils. Concentrations of the extractable Al, Fe, and co-dissolved C and N were determined to examine the mode and degree of organo-mineral associations as affected by soil acidity, depth, and tree species. We will report the results of these analyses to discuss how soil acidity controls the balance between organic matter decomposition and stabilization.

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# Mechanistic Shifts in Organic Carbon Stabilization in Black Soil under Acidification Stress Induced by Fertilization

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## ABSTRACT

The phaeozem in Northeast China contain a large amount of soil organic carbon (SOC), but there is an long-term excessive use of chemical fertilizers, which in turn causes soil acidification. The relationship between soil acidification and SOC stability remains unclear. This study, based on a 16-year field experiment with five degrees of soil acidification (6.54 to 5.32) induced by nitrogen fertilizer rates, analyzes changes in the stability mechanism of SOC using aggregate grading and $^{13}C$ NMR spectroscopy. Results demonstrated acidification-induced reductions in macroaggregates (>2 mm) by 4.8-14.6% and increases in aggregate instability indices (PAD, $E_{LT}$) by 9.7-13.4%. Mean weight diameter (MWD) and geometric mean diameter (GMD) exhibited significant declines ($p < 0.05$) with decreasing pH. According to the $^{13}C$ NMR analysis, the SOC was predominantly composed of O-alkyl carbon and aromatic carbon. At pH 5.32, the Alip/Arom values decreased, and the molecular structure of SOC became more complex under different levels of acidification. In addition, the increase of [Fe(Al)-OC] (31.4-71.9%) complex indicates a shift in the stability of organic carbon from physical protection to organic mineral binding. Overall, soil acidification resulted in the decline of soil aggregate stability and the increase in SOC aromaticity. This droves the shift of the stabilization mechanism of SOC in the black soil ecosystem of Northeast meadows from physical protection to chemical stability.

**Keywords:** Soil organic carbon; Soil acidification; Soil aggregates stability; Chemical stability; Microbial community

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# Discovering the molecular basis for carbon storage in soil for food security and climate change mitigation

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**ABSTRACT**

Soil organic carbon (SOC) is a fundamental component of the global carbon cycle, acting as both a major carbon sink and a key determinant of soil health. Thus, it is crucial to understand how carbon storage in soils is controlled. Recent studies have suggested that long-term SOC persistence is primarily regulated by microbial accessibility rather than intrinsic chemical recalcitrance of different compound classes [1]. However, the physico-chemical mechanisms protecting various SOC compounds [2,3] and the limits of soil stabilisation capacity remain unclear. If such limits exist, they will constrain the potential of land management to increase SOC storage. Moreover, the current key SOC models, such as Rothamsted C model (RothC), do not incorporate these limits.

This study combines physical fractionation methods separating soil aggregates and mineral-protected pools, with advanced compound-specific radiocarbon analysis (CSRA) to directly determine the residence time of different SOC compound classes with varying polarities and sizes. By utilising well-controlled modern and historical soils from Long-Term Experiments at Rothamsted Research (RRes), we aim to understand how different SOC compounds are stabilized, assess whether soils have a maximum capacity for carbon storage and if these limits are influenced by soil properties or management practices. Based on these new understandings, we aim to refine the RothC model to improve predictions of SOC sequestration, which will enhance land management strategies for long-term carbon storage.

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# Controls on Temperature Sensitivity of Soil Organic Carbon Decomposition Along a Volcanic Elevation Gradient in California

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**ABSTRACT**

Understanding the factors controlling the temperature sensitivity ($Q_{10}$) of soil organic carbon (SOC) decomposition is critical in the context of global warming. This study examines how elevation-driven variations in climate, mineral phases, and organic matter composition regulate $Q_{10}$.

Topsoil and subsoil samples were collected from 8 sites across an elevation gradient (200–2800 m) in the Sierra Nevada. The soils developed from andesitic lahar deposits under mean annual temperature and precipitation of 2.9–16.6°C and 670–1330 mm, respectively. SOC respiration was measured during laboratory incubations with moisture maintained at 55% water holding capacity at 25°C, 17.5°C, and 10°C. The decomposition curves of SOC were generated by fitting the respiration data to a kinetic model. $Q_{10}$ values were calculated for the cumulative decomposition over the entire incubation period, as well as for the decomposition rates on days 7, 28, and 343. Soil properties, including active Al/Fe (oxalate-extractable Al/Fe), were determined. The chemical composition of organic matter was evaluated using pyrolysis-GC/MS.

SOC and active Al/Fe ranged 20–114 and 3–35 g $kg^{-1}$ in topsoil and 14–71 and 3–31 g $kg^{-1}$ in subsoil, respectively, both peaking at mid-elevations (1600–2300 m). In the topsoil, $Q_{10}$ showed no evident correlation with active Al/Fe during the early incubation stage but developed a strong positive association in the later stage, whereas the subsoil exhibited a consistently strong correlation between $Q_{10}$ and active Al/Fe throughout the entire incubation period. These contrasting patterns indicate that mineral-organic associations in the subsoil exert a stronger influence on $Q_{10}$. Accordingly, the tighter organo-mineral binding in subsoil is likely a major driver of the higher temperature sensitivity. Despite these clear links to active Al/Fe, $Q_{10}$ showed no direct relationships with climate variables, pH, physical properties, or the chemical composition of organic matter. Collectively, these patterns suggest that organo-Al/Fe interactions enhance the temperature sensitivity of SOC decomposition by stabilizing the SOC pool and mediating more complex, high-activation-energy reactions.

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# Manganese oxides direct polyphenol carbon toward abiotic polymerization or oxidative decomposition: Effect of pH and molecular structure

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**ABSTRACT**

Polyphenols represent an important component of soil organic matter (SOM) that widely originates from plants. Birnessite, a ubiquitous manganese (Mn) oxide, effectively facilitates the oxidative decomposition and polymerization of polyphenols. However, the impact of pH and molecular structure of polyphenols on such processes, as well as the characterization of the degradation products, has not been fully elucidated. Therefore, we performed batch sorption experiments under environmentally relevant pH conditions to investigate the interactions between birnessite and two polyphenol isomers: catechol and hydroquinone. Results revealed that catechol was more effective in reducing Mn and dissolving Mn-oxide than hydroquinone, particularly under lower pH conditions. Correspondingly, a greater amount of carbon was lost from the aqueous system due to sorption and/or oxidative decomposition during catechol reactions than hydroquinone. Spectral data support the concomitant formation of polymers and aliphatic degradation products for both compounds studied. Two-dimensional nuclear magnetic resonance (NMR) and ultra high-performance liquid chromatography-high-resolution accurate mass (UHPLC-HRAM) spectrometry analysis provided direct molecular-scale evidence of pH-dependent reaction pathways. Overall, lower pH conditions increased the degree of oxidation and proportion of low-molecular-weight species formed. The ortho positioning of hydroxyl groups in catechol facilitated more effective complexation and electron transfer to birnessite than the para configuration of hydroxyls in hydroquinone. While alkaline pH (7–8) favored oxidative coupling and polymerization, forming high-molecular-weight oligomers. This study provides valuable insights into the fundamental, pH-controlled pathways of organo-mineral associations involving Mn-oxides and their role in (de)stabilizing SOM.

**Keywords:** polyphenol, oxidative decomposition, polymerization, carbon stabilization

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# $^{13}C$ tracing reveals organo-mineral regulation of carbon stabilization under ambient and elevated $CO_2$ levels

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## ABSTRACT

Mitigating climate change requires soil-based C removal strategies that do not depend on ever-increasing N inputs and their associated non-$CO_2$ emissions from fertilizer use. Biochar and Fe minerals are emerging as important levers for durable soil C storage because both can stabilize organic matter via organo–mineral associations and aggregate protection rather than through N-driven biomass accumulation. Although individual mechanisms of Fe- and biochar-mediated C stabilization are increasingly well understood, limited knowledge exists regarding their combined effects, especially with engineered Fe-modified biochars. Biochar may act as an electron shuttle that modulates Fe redox cycling and promotes the formation of Fe-bound organic C domains in amended soils. Conversely, Fe (hydr)oxides can precipitate on or around biochar particles and bridge them with fresh organic inputs, co-stabilizing biochar-derived and plant-derived C within Fe–C microdomains and soil aggregates.

In a 21-day incubation using an alkaline, sodic soil (pH 8), soil respiration was measured following amendment with goethite, an engineered Fe-enriched char (wheat straw, 500 °C, 120,000 mg/kg Fe), and its non-Fe enriched pair. Fe-enriched char was applied at 2% w/w; unmodified biochar and goethite were applied at rates matching the C and Fe supplied by Fe-enriched char (0.382% and 1.33% w/w, respectively). Four $^{13}C$-labelled model root exudates (glucose, oxalic acid, L-leucine, and salicylic acid) were added at 130 mg C per kg soil across four replicate microcosms per treatment. C stabilization was assessed by combining cumulative $CO_2$–C fluxes with $^{13}C$ source partitioning to quantify the proportion of amendment-derived versus exudate-derived C remaining in soil.

We revealed that Fe-enriched char best stabilized three of the four substrates (glucose, oxalic acid, and L-leucine), reducing cumulative $^{13}C$–$CO_2$ loss by approximately 6–57% relative to non-Fe enriched biochar. This broad response indicates that Fe-bearing phases on biochar surfaces provide sorptive and redox-active domains capable of protecting labile carbohydrates, low-molecular-weight organic acids, and simple N-containing compounds from rapid mineralization. In contrast, the structurally complex phenolic compound salicylic acid was most effectively stabilized by goethite, which reduced $^{13}C$–salicylic acid mineralization by approximately 48% relative to Fe-enriched char. This highlights a specific role for crystalline Fe oxides in binding and protecting aromatic molecules. Together, these patterns point to complementary mechanisms: Fe-modified biochar preferentially stabilizes a wide range of labile exudate C via Fe–organic complexes and electron-shuttling effects on Fe redox cycling, while discrete Fe minerals such as goethite are particularly important for protection of phenolic C within Fe–C microdomains and aggregates.

To further elucidate mechanisms of C stabilization under future climate scenarios, a steady-state [15 atom %] $^{13}C$-$CO_2$ growth chamber trial was undertaken to evaluate biochar and Fe-mediated stabilization (using the same amendments as the incubation study) in unplanted and wheat-planted systems under ambient (450 ppm), elevated (675 ppm), and extreme (900 ppm) $CO_2$ scenarios. In the unplanted system, autotropic $CO_2$ capture was quantified, while the planted system traced stabilization of photosynthetically fixed C. The allocation of new, native, and amendment-derived C across POM, MAOM, and Fe-bound SOC was quantified.

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# Mixing Rice straw with various N sources in a sandy soil: organic C stabilization and priming effect

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**ABSTRACT**

Cellulose–rich rice straw (RS) is readily decomposed with high C losses as $CO_2$ and low fraction stabilized in soil organic C (SOC). Mixing of RS with N stimulates microbial growth and turnover that can lead to retention of the straw–derived C in soil and decrease the priming effect (PE), i.e., stimulation of SOC decomposition by freshly added straw. We determined the effect of soil application of mixed RS with various N sources on decomposition–related microbial processes with the following hypotheses. (1) The addition of organic or mineral N together with RS will alter microbial processes, leading to higher microbial C storage efficiency (CSE), resulting in higher SOC stabilization compared with RS alone (2) the mixture of RS + N–rich groundnut stover (GN) will reduce PE compared to the RS and GN applied alone. A 112–day incubation microcosm experiment included unamended $^{13}C$–enriched C4 soil (CT), soil amended with single $^{13}C$–depleted residues of C3 plants, RS and GN, and the following combinations of N amendments with RS: RS+GN, and RS+ urea fertilizer. We determined soil microbiological parameters including $CO_2$–C evolution, microbial biomass (MB) C and N, microbial metabolic quotient ($qCO_2$) and PE. The mixture treatments had lower $CO_2$–C evolution than the single residue treatments starting from 42 days after amendment incorporation (DAI). Microbial biomass (MB) C and N were higher in mixed treatments than those of RS alone. Microbial metabolic quotient ($qCO_2$) (i.e., the inverse of CSE) decreased as decomposition proceeded. The mixed treatments had lower $qCO_2$ or higher CSE than RS alone at all decomposition stages. The mixture of RS+GN decreased PE below the single residue treatments from 21 until 112 DAI. We concluded that mixing RS with N-rich materials increased CSE relative to RS alone and RS mixed with groundnut reduced PE. The application of rice straw together with groundnut stover in sandy soils thus helps sequester C and decrease C losses as compared to RS alone.

# Conversion of coastal marshes to croplands shifts the pool, composition and functional groups of soil organic matter

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**ABSTRACT**

Reclamation of coastal marshes to croplands generally shrinks the pool of soil organic matter (SOM). However, it is not clear how marsh reclamation shifts the SOM composition (i.e., glycoproteins and iron-bound OM) and functional groups. Here, we investigated this issue in two coastal marshes (Qilihai, seasonally flooded; Beidagang, permanently flooded) and adjacent reclaimed croplands (over 60 years) on the coast of Bohai Bay, China. Two SOM fractions were separated by ultrasound: particulate (POM, > 0.053 mm) and mineral-associated carbon (MAOM, <0.053 mm). Reclamation reduced the contents of SOM (-8.7–96.4%) and glomalin-related soil proteins (GRSP, glycoproteins secreted by arbuscular mycorrhizal fungi) (-21.2–84.7%) in both bulk soil and its fractions, particularly at the Beidagang site. Reclamation suppressed iron-bound organic carbon (Fe-OM) in both bulk soil and its fractions at the Beidagang site, while having minimal effect at the Qilihai site, likely due to contrasting initial flooding regimes. Moreover, SOM increased with GRSP and amorphous iron at both sites (except for MAOM at the Qilihai site), and with Fe-OM exclusively at the Beidagang site. After reclamation, the relative absorbance of alcohol C-OH/C-NH decreased, while polysaccharide C-O increased, leading to a reduction in aromaticity with minimal impact on recalcitrance. Despite the initial differences in flooding conditions, both SOM and GRSP, along with aromaticity, decreased synergistically in bulk soil and MAOM following marsh reclamation. In contrast, the responses of Fe-OM varied depending on the distinct waterlogging conditions. These findings enhance our understanding of the interactions between SOM composition and functional groups during different floodplain wetland conversions and provide valuable insights for the management of coastal wetlands.

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# Influence on the structural stability of aggregates and soil organic carbon sequestration with different organic materials application: Analyzed from the perspective of the structure and properties of humic acid in aggregates

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## ABSTRACT

Soil aggregates stabilization and soil organic carbon (SOC) sequestration are essential for saline-alkali soil amelioration (Zhang et al. 2025), yet the role of humic acid (HA) remains unclear. A three-year field experiment investigated how the structure and properties of HA within aggregates influence SOC sequestration and aggregate stability under different organic materials applications. Treatments included no fertilization (Control), chemical fertilizer (NPK), organic fertilizer (OF), maize straw (MS) and cow manure (CM), among which the carbon (C) application of OF, MS and CM was 2000 kg C $ha^{-1}$. The results show that: Compared with Control, the mean weight diameter and SOC stock increased by 15.96% - 36.17% and 5.98%-10.38% with the organic materials application. Furthermore, these applications promoted the conversion of protein-like substances to humic-like substances, and enhanced the aromaticity, hydrophobicity and humification of HA. HA under OF was dominated by humic-like substances and fulvic-like substances, whereas protein-like substances were predominant under CM. HA in MS and OF treatments originated from a plant-microbial mixture, while in CM it was primarily from exogenous substances. The increase of Aliphatic-C and protein-like substances of HA in aggregates promoted soil agglomeration. Redundancy analysis revealed a strong correlation between MWD and the structure and properties of HA. In conclusion, the structure and proporties of HA are sensitive indicators for fertilizer management in saline-alkali soils, directly influencing SOC sequestration and aggregate stability.

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# Soil organic matter formation from high P organic amendments

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**ABSTRACT**

Soil organic matter (SOM) is a major determinant of soil fertility, as it regulates fundamental properties such as bulk density, water-holding capacity, aggregation and nutrient cycling. However, SOM declines in agricultural systems, reducing soil fertility and transforming soils from carbon (C) sinks into emitters. A common strategy to mitigate SOM losses is the amendment of soils with organic matter rich materials such as sewage sludge or compost, yet the underlying mechanisms remain poorly understood. Recent evidence suggests that phosphorus (P) in these materials is a key regulator of SOM dynamics[1]. We hypothesized that SOM formation and stabilization is influenced by the chemical characteristics of organic amendments. We developed a sodium polytungstate (SPT) based soil size-density fractionation method compatible with SOM and P analyses that yields six SOM fractions. This method was then applied to Luvisols from a two-decade long field experiment receiving sewage sludge or household waste compost, where sustained increases in SOM have been observed, as well as to unfertilized control soils. Coarse particles (50 µm-2 mm) were separated into fractions CL (< 1.8 g $cm^{-3}$), CDA (> 1.8 g $cm^{-3}$), and CDB (≫ 1.8 g $cm^{-3}$), while fine particles (< 50 µm) were separated into fractions FL (< 2.4 g $cm^{-3}$), FDA (> 2.4 g $cm^{-3}$), and FDB (≫ 2.4 g $cm^{-3}$). We calculated the recovery of C, N, P, and other elements fractions relative to the bulk soil, as well as their δ $^{15}N$. Organic amendments influenced soil C stocks, with compost amended soils reaching 3.5% C, sludge amended soils 2.2%, and unfertilized soils 1.2%. The C % in sludge amended soils is particularly notable given that, over two decades of annual applications, the sludge treatment received only one quarter of the cumulative C inputs received by the compost treatment[2]. The isotopic signatures of compost and sludge were reflected across all C containing fractions, demonstrating that fertilizer-derived C was incorporated throughout the soil matrix. We found that size-density fractions were influenced by the type of organic amendment: FL was proportionally larger under compost fertilization, whereas FDB was larger under sewage sludge fertilization. Fraction FDA despite representing only 15-22% of total soil mass, contained up to 50% of total soil C and N and approximately 30% of soil P. Sewage sludge fertilization resulted in greater C incorporation into FDB compared with compost, concurring with increased iron (Fe) and P recoveries in that fraction and treatment. Across treatments and in most fractions, C recoveries were strongly correlated with P recoveries ($R^2$= 0.74 - 0.85). Results indicate that the presence of additional elements in the amendments, such as P and Fe, may influence the amount of C that can be retained in soil. This finding opens the door to more detailed investigation aimed at elucidating the mechanisms linking C retention in soils to these elements.

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# Dual and divergent formation pathways govern the composition and origins of mineral-associated organic carbon

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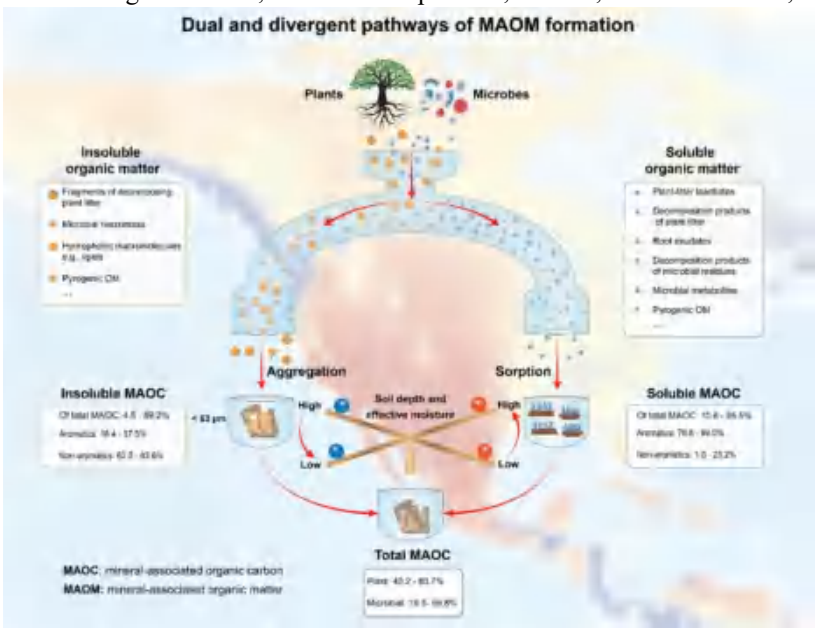
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## ABSTRACT

Mineral-associated organic matter (MAOM) is the largest and most stable soil carbon reservoir, playing a central role in soil health and climate mitigation. Yet, quantitative understanding is lacking for the two fundamental processes forming MAOM — sorption of dissolved organic matter (DOM) on mineral surfaces, and aggregation of insoluble particulate and hydrophobic materials with mineral particles in microaggregates (<53 μm) — and how each process incorporates plant- versus microbial-derived carbon. Analyzing soils from diverse ecosystems across North America, we found that both pathways substantially contributed to MAOM, with sorption accounting for 11–96% and aggregation for 5–89% of total MAOM carbon, depending on environmental context. Sorbed MAOM was highly enriched in phenolic and carboxyl functional groups, and lignin-, tannin- and condensed aromatics-like compounds, thereby primarily plant-derived. Aggregated MAOM, however, contained abundant alkyl groups and non-aromatic materials, hence primarily microbial-derived. Sorbed MAOM exhibited Langmuir- type saturation dynamics whereas aggregated MAOM did not saturate. Despite environmental factors strongly influenced the pathway dominance, the chemical composition of each fraction remained relatively consistent across ecosystems, reflecting joint controls of microbial processing, mineral sorption, and intrinsic chemical properties of organic compounds. These findings provide pathway-specific parameters for refining soil-carbon models and offer practical guidance for management strategies targeting long-term carbon sequestration.

**Keywords:** mineral-associated organic matter, chemical composition, sources, continental scale, FT-ICR MS, NMR



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# Ancient radiocarbon-free organic carbon as a pervasive bias in soil $^{14}$C-based turnover estimates

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## ABSTRACT

Radiocarbon ($^{14}$C) measurements are widely used to constrain soil organic carbon (SOC) turnover times and assess carbon persistence in soils. However, bulk SOC $^{14}$C signatures are increasingly recognized to be biased by the presence of ancient, radiocarbon-free organic carbon (aOC). This carbon pool is not involved in contemporary soil carbon cycling but inflates apparent SOC ages, contributing to discrepancies between radiocarbon observations and modelled soil carbon dynamics. In this study, we quantify aOC at the global scale using a linear mixing model applied to $^{14}$C data from 313 soil profiles (2,204 mineral soil layers) compiled from two global databases (ISRaD and LSCE). The approach separates radiocarbon-dead aOC from biologically active SOC, allowing a reassessment of SOC radiocarbon ages commonly interpreted as turnover times.

Our results (Copard et al., 2025) show that aOC is ubiquitous in soils, with a mean concentration of 2.4 ± 3.2 mg $g^{-1}$. Its contribution increases systematically with depth, representing on average ~11% of SOC in topsoils (0–30 cm), ~27% in subsoils (30–100 cm), and >50% in deep soil horizons (>100 cm). Pedological context controls aOC abundance: high contributions occur in Andosols and Cryosols, while parent material and long-term pedogenesis explain variability across WRB soil groups. Correcting bulk $^{14}$C signatures for aOC substantially revises SOC radiocarbon age estimates. The mean corrected age of reactive SOC to 1 m depth is ~290 years, contrasting sharply with previously reported values of 3000–5000 years inferred from uncorrected bulk $^{14}$C. These revised ages are consistent with independent pedological and isotopic constraints ($^{13}$C, $^{36}$Cl) and reconcile radiocarbon observations with Earth System Model representations of soil carbon turnover.

The widespread presence of aOC necessitates its explicit consideration in the interpretation of soil radiocarbon data. Incorporating parent material, pedogenesis duration, soil depth and soil classification is critical to avoid systematic overestimation of SOC persistence and to strengthen the application of radiocarbon constraints in soil carbon modelling. This will provide a more realistic framework for assessing soil carbon turnover, sequestration potential, and potentially long-term climate mitigation strategies.

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# Soil Carbon Stabilization and Site-Specific Drivers in Large-Diameter Timber Plantations of Southern China's Acidic Red Soils

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## ABSTRACT

Southern China's red soil region is confronted with soil acidification and low organic carbon stability, which constrain long-term carbon sequestration. Establishing large-diameter timber plantations is recognized as a promising approach to enhance soil carbon storage and support global climate mitigation efforts. To clarify the mechanisms of soil organic carbon stabilization in these plantations and to identify the site-specific conditions that optimize their carbon-sink function, this study was conducted in Guangdong Province, a typical area within this region.

Four major plantation species, namely *Cunninghamia lanceolata*, *Castanopsis hystrix*, *Michelia macclurei*, and *Manglietia glauca*, across fourteen state-owned forest farms were investigated. Field surveys and laboratory analyses were performed to determine soil organic carbon density as an indicator of carbon sequestration capacity, the carbon pool management index as a measure of carbon pool stability, and key soil organic carbon fractions including active components such as particulate organic carbon and permanganate-oxidizable carbon alongside the passive mineral-associated organic carbon fraction. Edaphic properties and topographic variables were integrated to develop predictive models for carbon storage through structural equation modeling and principal component analysis.Soil organic carbon density in the top one-meter layer across all four plantation types significantly exceeded the provincial forest average of ten point four four megagrams per hectare. *Castanopsis hystrix* stands achieved the highest soil organic carbon density at forty-two point four five megagrams per hectare, followed by *Michelia macclurei*, *Cunninghamia lanceolata*, and *Manglietia glauca*. All plantations exhibited obvious surface aggregation of soil organic carbon. Carbon pool management index values greater than one for both *Cunninghamia lanceolata* and *Castanopsis hystrix* indicated more stable soil carbon pools compared to forests not managed for large-diameter timber. Mineral-associated organic carbon, the dominant passive fraction accounting for over seventy percent of total soil organic carbon, served as the core of carbon stabilization. Distinct spatial heterogeneity was observed: particulate organic carbon concentrations were higher in central Guangdong than in eastern and western regions; mineral-associated organic carbon accumulation was prominent in northern and eastern Guangdong; and permanganate-oxidizable carbon, an active fraction, was elevated in western and northern regions.Structural equation modeling revealed that soil organic carbon storage was positively regulated by soil pH, soil organic carbon content, bulk density, and latitude, while being negatively affected by stand age, total potassium, available iron, and slope position. Principal component analysis identified northern Guangdong, characterized by brownish-red or brownish-yellow soils, mid-elevation, and a soil pH ranging from five point zero to five point five, as the optimal region for *Cunninghamia lanceolata*, *Michelia macclurei*, and *Manglietia glauca*. In contrast, *Castanopsis hystrix* performed best in eastern Guangdong under conditions of moderate slope, weak acidity, and high soil organic carbon content. Regarding the comprehensive performance integrating soil carbon sequestration capacity indicated by carbon density and carbon stabilization indicated by the carbon pool management index and mineral-associated organic carbon dominance, the order was *Cunninghamia lanceolata*, followed by *Castanopsis hystrix*, then *Manglietia glauca*, and finally *Michelia macclurei*.

This study elucidates the key mechanisms and spatial patterns of soil organic carbon stabilization in large-diameter timber plantations of southern China's acidic red soil region. The findings provide a scientific basis for species-specific plantation layout and sustainable management strategies, facilitating enhanced carbon sequestration and improved soil health under acidic soil conditions.

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# Soil Carbon Stocks and Stable Isotope Profiles in South Korean Forested Wetlands across Successional Stages

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**ABSTRACT**

Wetlands play a critical role in climate change mitigation and adaptation, making their conservation and restoration essential strategies for climate action. However, research evaluating carbon storage and the mitigation value of forested wetlands remains relatively scarce. While studies on carbon stocks and fluxes in agricultural and forest soils are well-established, and research on coastal, riparian, and floodplain wetlands has progressed, the soil carbon of forested wetlands remains poorly documented. This study analyzed soil carbon stocks across six forested wetland sites in South Korea, representing different successional stages, to propose frameworks for their valuation in climate change mitigation. Ten soil cores (up to 1 m depth) were collected per site to analyze the vertical profiles of carbon, nitrogen, and their stable isotopes. Additionally, carbon stocks in aboveground biomass, including woody and herbaceous vegetation and the forest floor, were assessed through field surveys and sampling. The mean soil carbon stock was 434 Mg C $ha^{-1}$, which is approximately three times greater than typical forest soils and twice that of inland wetlands in South Korea. Soil carbon stocks ranged from 221 to 888 Mg C $ha^{-1}$ across the sites; notably, natural forested wetlands (589 Mg C $ha^{-1}$) harbored twice as much soil carbon as abandoned paddy forested wetlands (279 Mg C $ha^{-1}$). This disparity suggests significant potential for continuous carbon sequestration as abandoned paddies transition into natural forested states. Stable carbon isotope ratios ($\delta^{13}C$) ranged from –27‰ to –25‰, generally increasing with soil depth. These isotopic profiles indicated slower soil carbon turnover rates in natural forested wetlands, suggesting superior long-term carbon storage and climate mitigation capacity. Although forested wetlands occupy a small fraction of the total land area, this study confirms their high localized carbon storage potential. Therefore, we propose sustained monitoring and management of these sites as vital carbon sinks.

**Acknowledgments**

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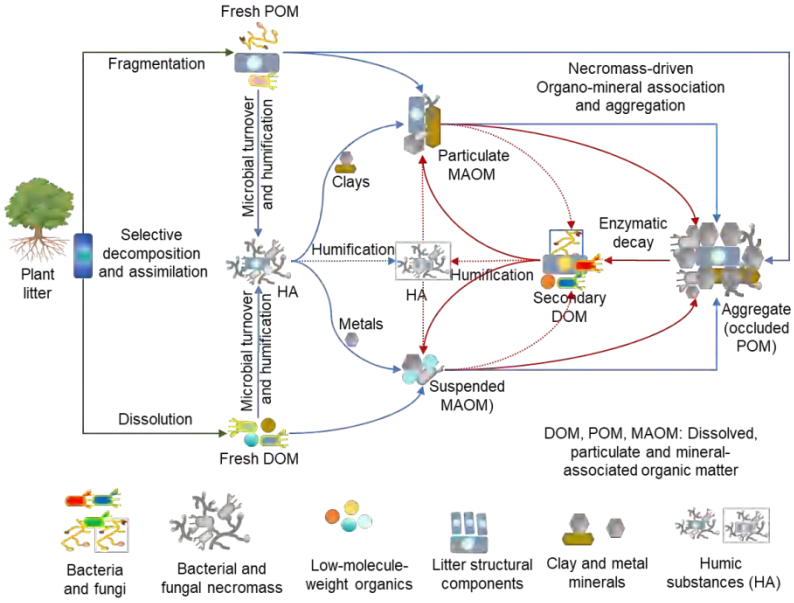
# Particulate pathway dominates mineral-associated organic matter formation and transformation

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## ABSTRACT

Plant litter is the dominant source of organic carbon entering soils, yet the mechanisms by which litter-derived carbon is transformed into persistent soil organic matter (SOM) remain incompletely resolved. Prevailing frameworks emphasize aqueous-phase processes, either through chemical humification in solution or through the selective sorption of dissolved organic matter (DOM) onto mineral surfaces, but largely overlook the potential for a direct particulate pathway in which litter and particulate organic matter (POM) are transformed into mineral-associated organic matter (MAOM) without prior dissolution or major disruptive events. To fill this gap, we incubated model soils consisting of individual 2:1 and 1:1 clay minerals mixed with wheat (Triticum aestivum) plant litter for 180 days. Using a combination of SOM physical fractionation, FT-ICR MS, solid-state $^{13}$C NMR spectroscopy, micro-scale FTIR imaging, and causal (cross-lagged panel model, CLPM) modeling, we provide direct evidence that a particulate pathway dominates the formation and renewal of mineral-associated organic matter (MAOM). The dynamics of SOM physical fractions revealed a strong coupling between POM and MAOM accumulation with no corresponding buildup of DOM, indicating that MAOM formation does not require a dissolved intermediate. FT-ICR MS spectrum showed that MAOM is structurally distinct from DOM (Mean Jaccard, 0.38). In contrast, solid-state $^{13}$C NMR spectra spectrum showed that POM and MAOM exhibiting strong linear relationships across multiple carbon functional groups ($R^2$, 0.79~0.89). FT-IR microscopy further demonstrated intimate spatial associations between particulate litter residues and mineral surfaces, consistent with direct physical transfer. CLPM models confirmed that POM exerts a dominant and directional influence on MAOM dynamics, whereas DOM contributes weakly. Together, these results demonstrate that structural litter residues can be directly transformed into mineral-associated organic matter without prior solubilization or disruptive release events. This particulate pathway reconciles classical humification concepts with contemporary mineral-association models and reveals an overlooked mechanism governing long-term soil carbon persistence. Incorporating this pathway into soil carbon frameworks will improve predictions of carbon storage and stability across ecosystems.




**Graphical ABSTRACT**

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# Effects of organic amendments on soil carbon stocks and their distribution between particle and mineral-associated organic carbons in a red pepper field

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## ABSTRACT

Soil organic matter (SOM) is fundamental for maintaining crop productivity and enhancing carbon (C) sequestration in agricultural soils, contributing significantly to climate change mitigation. SOM is commonly fractionated into particulate organic matter (POM) and mineral-associated organic matter (MAOM) to compare forms of potential soil C storage. However, related studies remain limited. In this study, six treatments were installed and maintained for 3 years in a red pepper cultivated field: no fertilizer (NF), only inorganic fertilizer (NPK), red pepper residue (R), compost (Com), rice hull biochar (RB), woody biochar (WB). Organic matters (OM) were annually incorporated as a basal application at 5 Mg d.w $ha^{-1}$ under the recommended inorganic fertilization level. To evaluate changes in soil C stocks in the surface soil (0-15 cm), bulk density and C content were measured separately for the 0-5 and 5-15 cm layer, and soil C stock were calculated. Then, SOM was fractionated into POM [light fraction (LF) and sand-sized fraction] and MAOM [silt- and clay-sized fraction]. Moreover, POM-C and MAOM-C contributions were calculated as the proportion of fraction-associated C relative to total SOC, indicating that these metrics reflect how soil C is partitioned between POM and MAOM pools. Soil C stocks in surface soil significantly increased with OM incorporations and showed the highest C accumulations (expressed in Mg C $ha^{-1}$) in biochar treatments (50.6 ~ 50.8) followed by Com (49.1), R (46.9) compared with the non-OM treatment (NF and NPK, 44.7). These results indicate that approximately 0.73 ~ 2.04 Mg C $ha^{-1}$ was annually accumulated with OM additions into a pepper field. OM applications altered the distribution of soil C fractions, with significant effects on the POM pools as the active C. OM applications gradually increased in the LF proportion, and notable increases were observed in the biochar treatments (2.1 ~ 3.4%) compared with the NPK treatment. C concentrations tend to increase in the LF under OM application compared with the non-OM application, while MAOM showed no significant difference among treatment. The contribution of POM-C to total SOC increased with OM incorporations and showed the highest proportions in biochar treatment (36.1 ~ 45.1%), and then followed by Com (31.8%), R (30.7%), NPK (26.1%), and NF (24.0%). Therefore, our results indicate that increases in soil C stocks under OM applications were primarily driven by enhanced POM-C accumulation. Future research is needed to evaluate whether the C accumulation under OM application contributes long-term soil C pools, considering the chemically recalcitrant characteristic of OM-derived C.

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# Iron-mediated mechanisms of soil organic carbon stabilization in paddy soils under warming and altered flooding

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## ABSTRACT

Paddy soils represent a globally significant agroecosystem, functioning both as the primary environment for irrigated rice (*Oryza sativa* L.) production and as extensive anthropogenic wetlands with a major role in soil organic carbon (SOC) sequestration. Under climate change, increasing temperatures and reduced water availability threaten soil health, carbon (C) stability, and the long-term resilience of these systems.

This study evaluates how anaerobic digestate application influences soil organic matter (SOM) dynamics in paddy soils under simulated climate stress. A factorial field experiment tested amendment application (digestate, DS; unamended control, UN), temperature (ambient, AM; warming, +2 °C, WR), and water regime (normal flooding, NF; reduced flooding, - 30%, RF). SOM was fractionated into particulate (POM) and mineral-associated organic matter (MAOM) pools, which were characterized using Fe K-edge XANES and $k^2$-weighted EXAFS to resolve Fe speciation and coordination environments controlling SOC stabilization.

Across treatments, SOC declined under warming, with WR plots losing up to 15% more SOC than AM, while digestate under NF partially mitigated SOC losses and reduced C/N ratios, possibly indicating enhanced microbial processing.

XANES revealed strong fraction- and management-dependent shifts in Fe speciation, showing that POM was enriched in redox-sensitive Fe phases and Fe-organic complexes that responded markedly to reduced flooding and warming, whereas MAOM was dominated by illite-associated Fe and Fe (III) oxyhydroxides. Complementarily, $k^2$-weighted EXAFS resolved the short-range Fe coordination environment, indicating that POM contained mixed crystalline Fe (III) phases (hematite and lepidocrocite) embedded within a variable mineral matrix, while MAOM was systematically enriched in poorly ordered Fe (III) phases, including ferrihydrite-like and Fe (III)-organic associations, indicative of persistent mineral-protected C pools. Together, XANES and EXAFS demonstrate that climate stress primarily destabilizes SOC by disrupting redox-controlled Fe-organic associations in the labile POM fraction, whereas long-term carbon persistence under future warming scenarios depends on the maintenance of Fe (III) oxyhydroxide-mediated protection within MAOM, only weakly modulated by organic amendment and water regime.

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# Distribution Patterns and Their Controlling Factors of Phytolith Abundance and Carbon Content in Mollisols (Phaeozems) of Northeast China

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## ABSTRACT

The high content and long-term stability of soil organic carbon (SOC) are pivotal to sustaining the ecological functions and agricultural fertility of Mollisols, whose organic matter derives predominantly from grassland vegetation. Notably, phytoliths—primarily produced by herbaceous plants—exhibit remarkable resistance to corrosion and decomposition. They act as robust proxies for reconstructing past vegetation and tracing SOC sources, while enhancing long-term SOC stability via occluded carbon (PhytOC). To elucidate the indicative significance of phytoliths for black soil organic carbon stability, we collected 30 pairs of cropland and non-cropland topsoil samples and six soil profiles across Mollisols (Phaeozems) region of Northeast China, then investigated the distribution characteristics of phytoliths and PhytOC in topsoil samples and soil profiles. In cropland, phytoliths and PhytOC contents were 13.5 ± 4.7 g·kg$^{-1}$ soil (mean ± SD) and 0.06 ± 0.02 g C·kg$^{-1}$ soil, respectively. With ~47°N as the geographical boundary, phytolith contents in the northern cropland samples were significantly higher than those in the southern region. In non-cropland, mean phytolith and PhytOC contents were 15.0 ± 3.5 g·kg$^{-1}$ soil and 0.08 ± 0.03 g C·kg$^{-1}$ soil, respectively. No significant difference was observed in their distribution along the latitudinal gradient, while PhytOC content peaked at 0.65 g C·kg$^{-1}$ soil. Moreover, soil phytolith and PhytOC contents showed no significant difference between cropland and non-cropland soils. Partial least squares structural equation modeling (PLS-SEM) reveals that soil parameters are the primary drivers of variations in phytolith and PhytOC contents in non-cropland soils. Specifically, soil pH negatively affects phytolith content, while soil nutrients significantly promote its accumulation; precipitation indirectly influences soil phytolith content by modifying soil pH and nutrient availability. Soil phytolith content was predominantly driven by long-term cultivation rather than inherent soil factors. With increasing soil depth, SOC, mineral-associated organic carbon (MAOC) and PhytOC contents decreased by 79%, 71%, and 50% on average, respectively. However, the PhytOC/SOC and PhytOC/MAOC ratios increased significantly with depth, both peaking at ~4%. Furthermore, the phytolith and PhytOC stocks in the top ~1 m soil ranged from 12.4 to 34.5 kg·m$^{-2}$ and 0.05 to 0.37 kg C·m$^{-2}$, respectively. Measured PhytOC stocks were substantially greater than values reported for other global grasslands (e.g., 0.039 kg C·m$^{-2}$ in northern grasslands and 0.033 kg C·m$^{-2}$ in temperate grasslands). Our results underscore that phytoliths are an important carbon fraction for long-term carbon sequestration in Mollisols, providing a scientific basis for optimizing land management to improve agricultural soil carbon stability.

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# Iron oxides promote stable soil organic carbon sequestration in rice paddies

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**ABSTRACT**

Soil organic carbon (SOC) sequestration can mitigate climate change, but the development of effective management strategies is limited by a poor understanding of the factors controlling organic matter stabilization in soils. SOC sequestration occurs through interactions between organic matter and soil minerals, but the role of iron (Fe) oxides in this process is not well understood. This is particularly true in rice paddies, where waterlogging alters Fe oxide chemistry in ways that might promote SOC sequestration. For example, redox fluctuations promote the formation of amorphous Fe oxides, which have a higher surface area for sorption than crystalline Fe, and create complexes between organic matter and Fe oxides that resist decomposition. To estimate the influence of Fe compounds on SOC accumulation in rice paddies, we determined Fe and SOC pools in rice paddy and upland soils throughout South Korea. We isolated particulate organic C (POC) and mineral-associated organic C (MAOC), and quantified Fe oxides in amorphous (extracted in acid ammonium oxalate), organically associated (extracted in sodium pyrophosphate) and total pedogenic (extractable in sodium dithionite) forms. SOC is greater in paddy than in upland soils in Korea by an average of 2.0 g C $kg^{-1}$. Paddy soils also contain a greater proportion of SOC as MAOC compared to upland soils, indicating more stable SOC in rice paddies. Paddy soils contain higher concentrations of organically associated Fe than upland soils (3.2 vs 2.3 g Fe $kg^{-1}$, respectively) and a greater proportion of their pedogenic Fe is in amorphous forms (i.e., oxalate-Fe / dithionite-Fe × 100; 25% v 21% in paddy and upland soils, respectively). Overall, these results suggest that fluctuating anaerobic and aerobic conditions in rice paddies promote SOC stability through interactions with Fe oxides, predominantly via organic matter–Fe complexation. Future research should develop management practices that promote these mechanisms for effective SOC sequestration.

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# Assessment of carbon stock, stabilization, and soil aggregate structure in different Mediterranean agro-ecosystems

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## ABSTRACT

The study, conducted within the EU PRIMA project ReCROP, aimed to evaluate the effectiveness of sustainable practices - including cover cropping, soil amendments, and microbial inoculants such as mycorrhizal fungi (MF) and plant growth-promoting bacteria (PGPB)- on soil carbon stocks, carbon stabilization, and soil aggregate structure in Mediterranean agroecosystems. To investigate how these treatments induce changes in soil physicochemical properties and assess their potential for soil carbon sequestration, advanced analytical techniques were employed. These included Low-Temperature Ashing (LTA), Fourier Transform Infrared (FTIR) spectroscopy combined with Photoacoustic Spectroscopy (PAS), and laser granulometry.

LTA treatments, performed using self-assembled equipment as described by D'Acqui et al. (1), allowed for the controlled removal of organic matter (OM) from soil aggregates at low temperatures. Organic carbon (C) was measured in untreated soil samples (0 hours) and in samples exposed to treatment durations of 5, 24, and 48 hours. After 48 hours, the residual carbon was considered to be physically protected within the aggregates. PAS was used to analyze the composition of soil organic matter (SOM) on the surface of both untreated and LTA-treated aggregates through FTIR-PAS spectra interpretation.

Both dry and pre-wetted aggregates gently sprayed with deionized water were immersed in distilled water, subjected to ultrasound treatment, and then analyzed with a laser granulometer to determine particle and aggregate size distribution.

The results demonstrate that treatments increasing the content of physically protected carbon enhance the stability of dry soil aggregates, which is critical for reducing erosion and conserving water. When soils are dry and subjected to rapid wetting, they are particularly vulnerable to slaking, a process where soil aggregates disintegrate due to their inability to withstand water-induced stress, resulting in the breakdown of soil structure. Additionally, the findings emphasize the importance of adopting practices that promote the transformation of organic matter into more stable, high-quality forms, such as physically protected organic matter. These improvements contribute to greater soil stability and overall soil health, promoting sustainable land management in Mediterranean agroecosystems.

**Acknowledgments**

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# From waste to carbon sink: mineral-organic coupling in technosols

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## ABSTRACT

Converting organic solid wastes into functional technosols offers a promising pathway for carbon neutrality, yet the mechanisms governing mineral-associated organic carbon (MAOC) formation in such engineered soil systems remain poorly understood. Here, we present a comprehensive framework elucidating MAOC stabilization dynamics through systematic manipulation of biomass quality gradients (distiller's grains, cotton/maize/wheat straw with lignin contents of 14.6-26.8% and C/N ratios of 3.78-115.51), reactive mineral assemblages (montmorillonite, goethite, boehmite, ferrihydrite, and their combinations), and microbial inoculants across 90-day incubations at 15°C, 25°C, and 35°C.

Our results demonstrate that MAOC accumulation efficiency varies 3.2-fold across biomass types, with lignin-rich substrates (>22% lignin) yielding 47.3±4.8 g MAOC/kg compared to 14.7±2.1 g/kg for low-lignin materials after 90 days. Iron (oxyhydr)oxides exhibited superior organic carbon binding capacity, with goethite-amended technosols accumulating 156% more MAOC than montmorillonite-only treatments. Critically, we identified a synergistic mineral-microbial coupling mechanism: combining 5% ferrihydrite with microbial inoculants ($2\times10^{10}$ CFU/g including Bacillus, Trichoderma, and thermophilic bacteria) enhanced MAOC formation by 73.4% compared to single-factor treatments.

The microbial carbon pump contributed 38.6±5.2% of total MAOC through necromass deposition, with bacterial residue carbon showing stronger correlation with MAOC ($r=0.82$, $P<0.001$) than fungal residues ($r=0.54$, $P<0.01$). Extracellular polymeric substances concentration exhibited significant positive correlation with MAOC formation ($r=0.76$, $P<0.001$), while reactive oxygen species -mediated oxidation facilitated the transformation of aromatic compounds into mineral-binding carboxylated derivatives, contributing 12.3±2.8% of newly formed MAOC. Enzyme activity profiling revealed β-glucosidase ($r=0.71$, $P<0.01$) and phenol oxidase ($r=0.68$, $P<0.01$) as key regulators of MAOC-precursor generation. MAOC preferentially accumulated at mineral-organic interfaces with organic layer thicknesses of 2.8-15.6 nm on iron oxide surfaces. Temperature sensitivity analysis showed that MAOC formation was maximized at 25°C ($Q_{10}=1.42\pm0.18$), while higher temperatures (35°C) accelerated POC decomposition but reduced MAOC stabilization efficiency by 23.7%. Soil aggregate analysis demonstrated that macroaggregates (>250 μm) protected 52-68% of total MAOC, with aggregate-occluded MAOC showing 2.3-fold longer mean residence time than free MAOC. Our findings establish a mechanistic framework for engineering carbon-stabilizing technosols from organic wastes.

**Keywords:** Technosol; Mineral-associated organic carbon; Microbial carbon pump; Carbon sequestration;

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# Tree species traits interact with site properties to shape soil organic matter composition

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## ABSTRACT

Soil organic matter (SOM) represents a major carbon reservoir in forest ecosystems, yet the respective influences of tree species and site conditions on SOM molecular composition remain insufficiently resolved. To address this gap, this study examined SOM biochemical signatures across five European common gardens. Topsoil samples were collected beneath adjacent stands of broadleaf and coniferous species differing in their symbiotic microbial associations—arbuscular mycorrhizae (AM) or ectomycorrhizae (ECM)—with some species additionally forming associations with nitrogen-fixing bacteria. SOM biochemical composition was characterized using pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS).

Tree species significantly shaped SOM origin and composition through their litter traits and associated microbiomes, while soil properties further modulated these effects. N-fixing ECM broadleaves enriched SOM in microbial-derived N-compounds. Topsoils under AM trees also showed higher contents of microbial-derived N-compounds compared to ECM trees, and—contrary to common expectations—AM soils were enriched in lignocellulosic residues.

Under conifers, SOM was enriched in aliphatic compounds and depleted in lignin relative to broadleaves in temperate sites, whereas the opposite trend was observed in the boreal site. Coarse-textured soils enriched in poorly crystalline oxides displayed a relative enrichment in aliphatics, while fine-textured soils rich in base cations selectively retained microbial-derived N-compounds and lignocellulosic residues.

The molecular fingerprint generated by Py-GC/MS demonstrated that lignocellulosic residues preferentially accumulate under AM- compared to ECM-associated trees in the studied soils, contrary to what is commonly inferred from forest floor observations or the use of N-related proxy analysis (such as C:N or amino-sugars). The study demonstrated that tree trait imprint on SOM composition is further modified by soil properties that determine the selective preservation of molecules. The presence of base cations, in conjunction with a finely textured phase, enhanced the mineral protection of lignocellulose and microbial-derived N compounds. It was also probable that the N-fertility inherited from a former agricultural use of the soil contributed to the non-degradation of lignin residues and microbial-derived N compounds. In soils enriched in poorly crystalline oxides, no plant or microbial preferential origin for N-compounds and polysaccharides was detected, while aliphatics were preserved due to thermodynamic limitations prevailing in such soils. Overall, the Py-GC/MS molecular fingerprint revealed the complexity of SOM formation pathways and highlighted how interactions between tree functional traits and soil mineral characteristics jointly determine the fate of plant- and microbial-derived residues in forest topsoils.

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# Fresh Plant Residues Drive Fungal Necromass Carbon Turnover to Stabilize Organic Carbon throughout the Soil Profile

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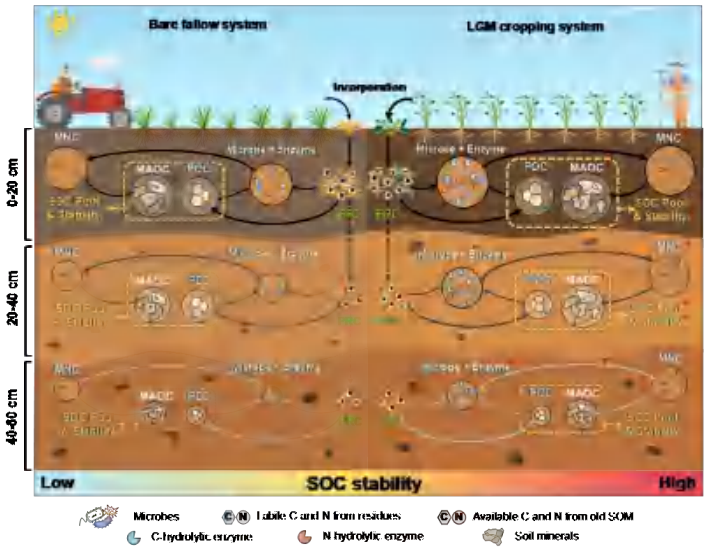
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**ABSTRACT**

Soil organic carbon (SOC) sequestration is essential for mitigating climate change and sustaining soil productivity in agricultural systems. Microbial necromass carbon (MNC) and plant residue-derived carbon (PRC) represent crucial stable fractions of SOC. However, it remains uncertain how fresh residues from green manure (GM) crops combined with nitrogen (N) fertilizer application influence the relative contributions and stabilization of microbial- versus plant-derived C in SOC, especially within deeper soil layers in drylands. To address this knowledge gap, a 16-year field experiment was conducted in China, comparing a rotation system of winter wheat (*Triticum aestivum* L.) with soybean [*Glycine max* (L.) Merr] versus a traditional fallow-wheat (FW) system, both subjected to two N fertilizer treatments (0 and 162 kg N $ha^{-1}$). Results demonstrated that the LGM rotation substantially enhanced SOC and mineral-associated organic C (MAOC) concentrations by 17.2-19.2% and 24.6-34.6%, respectively, in the 0-40 cm soil profile. However, particulate organic C (POC) was notably reduced at the depths of 20-40 cm. Notably, LGM crops significantly increased fungal necromass C (FNC) content by 39.7-65.1% and enhanced its contribution to SOC by 31-42%, driven by fungal-dominated microbial transformation of PRC into stable MNC via upregulated C-acquiring enzymes. Conversely, long-term N fertilization increased MAOC by 13.7-21.2%, but reduced MNC contribution to SOC. The observed reduction in POC was attributed to a shift toward alternative stabilization mechanisms, along with changes in microbial metabolism favoring rapid C turnover, thereby decreasing FNC and bacterial necromass C (BNC) at greater soil depths. Partial least squares path models (PLS-PMs) confirmed a significant positive total effect of LGM implementation on MNC, mediated through enhanced microbial biomass and C enzyme activities, whereas N fertilizer input exhibited an indirect negative influence. In summary, sustained cultivation of LGMs effectively promoted SOC stabilization through fungal-mediated MNC formation, while inorganic N fertilization impaired MNC accumulation. Optimizing LGM integration with reduced N application is beneficial for enhancing SOC sequestration and stability in the dryland agroecosystems.

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The National Key Research and Development Program of China (2021YFD1700200, 2023YFD1900900), the Chinese National Natural Science Foundation (Grant No. 31801942), the Fundamental Research Funds for the Central Universities (Grant No. 2452017042), and the earmarked fund for China Agricultural Research System-Green manure (CARS-22) provided financial support for this study.



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# A mechanistic investigation into the influence of mineral surface carbon loading on the formation of soil organic carbon

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**ABSTRACT**

Soil organic carbon (SOC) is the cornerstone of soil multifunctionality, underpinning plant production and the provision of food and fiber. As the largest active terrestrial carbon pool, SOC also drives negative climate feedbacks by sequestering atmospheric $CO_2$. Enhancing SOC sequestration is therefore critical for safeguarding food security and mitigating climate change. However, the capacity of soils to sequester additional SOC remains controversial, largely due to the ambiguous role of existing SOC in regulating new SOC formation. Traditional paradigms argue that existing carbon occupies vacant mineral surface sites (key for organo-mineral association formation), thereby limiting new SOC retention. In contrast, recent studies suggest existing SOC can facilitate extra carbon storage via organo-organo interactions. Resolving this contradiction is essential for accurately evaluating SOC sequestration potential and developing effective carbon-enhancing strategies.

Here, we investigated how mineral surface carbon loading (defined as the ratio of SOC to mineral specific surface area) regulates SOC formation via two key pathways: direct sorption (using $^{13}C$-labeled batch adsorption experiments) and in vivo microbial turnover (using microcosm experiments).

For both pathways, increased mineral surface carbon loading inhibited SOC formation—by reducing exogenous organic carbon retention and promoting the release/decomposition of native SOC. These results indicate that existing SOC has a limited capacity to host additional carbon, even with evidence of organo-organo interactions. Notably, in calcareous soils, exchangeable calcium exerted a more dominant regulatory role in microbial turnover-mediated SOC formation than mineral surface carbon loading. This finding reveals an unforeseen alternative mechanism of SOC formation, complementing the prevailing organo-mineral-centric framework for calcareous soils.

Our results provide novel mechanistic insights into the factors controlling SOC sequestration, offering critical implications for accurately assessing soil carbon sequestration potential and guiding targeted carbon management strategies.

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# Effects of carbon-equal straw return on active organic carbon fractions in the black soil plow layer and maize growth

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## ABSTRACT

Soil organic carbon (SOC) is one of the most critical carbon pools in soil ecosystems, playing a vital role in maintaining soil fertility and ecosystem functions. The Northeast Black Soil Region is an important granary in China, however, affected by environmental and anthropogenic factors, the region is facing a series of issues such as declining soil organic matter content, reduced fertility, and soil degradation, which lead to a significant reduction in crop yields. Therefore, how to efficiently increase the SOC content and soil quality, and thereby improve crop yields, is an urgent issue to be resolved. To address this, the experiment was initiated in 2022. With straw leaving field as the control (CK), five straw returning methods were set up: straw crushing and returning to field (CR), straw crushing and returning to field + straw decomposing agent (DA), cattle manure returning to field (CM), straw composting and returning to field (SC) and straw biochar returning to field (BC) By constructing an equal-carbon-content straw returning experimental system, this study measured SOC and its active fractions, soil physical structure, biological properties, and maize growth indicators at different growth stages of maize. The study compared and analyzed the dynamic changes in SOC and its active fractions under different straw returning methods with equal carbon content and explored the synergistic relationship between soil properties and maize growth to elucidate the regulatory mechanisms of different straw returning methods on maize yield. In summary, different straw returning methods can enhance both soil active organic carbon fractions and maize yield, but each method exhibited unique characteristics. The DA treatment significantly increased soil organic carbon content and the soil carbon pool index at the jointing and maturity stages and elevated the activities of four carbon-degrading enzymes throughout the maize growth period, however, it had certain destructive effects on soil physical structure in the short term. Similarly, the CR and BC treatments also exhibited some destructive impacts on soil physical structure in the short term. The CM treatment improved soil physical structure and enhanced polyphenol oxidase (PPO) activity throughout the maize growth period, but had relatively lower efficiency in increasing SOC and the soil carbon pool index in the short term. The SC treatment also improved soil physical structure, increased the activities of four carbon-degrading enzymes, and significantly increased SOC content and the soil carbon pool index during the large trumpet and maturity stages. Overall, under short-term straw returning conditions, the SC treatment effectively improved soil physical structure, while also having the potential to enhance soil carbon sequestration capacity and promote maize growth and yield. These findings provide significant data support for optimizing straw returning methods and improving soil quality in the short term in the Northeast Black Soil Region.

**Acknowledgments**

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# Soil Organic Carbon Fraction Dynamics Across Paddy Soil Profiles: A Critical Role of Parent Material

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**ABSTRACT**

Paddy soils evolve from diverse parent materials, whose legacy—particularly in terms of soil texture and elemental composition—fundamentally shapes their pedogenic trajectory and governs the accumulation of organic carbon (OC). However, the specific influence of parent material on the distribution of key functional OC pools—particulate (POC) and mineral-associated organic carbon (MAOC)—throughout soil profiles remains poorly understood. To address this knowledge gap, we investigated paddy soils derived from three major parent materials in the Chengdu Plain: Holocene alluvial deposits, Pleistocene glaciofluvial deposits, and Chengdu clay (loess deposits). Soil samples were collected from different genetic horizons down to a 1-meter depth and analyzed for total soil OC, dissolved OC, POC, MAOC, and key regulators including pH, cation exchange capacity, texture, and metal ion content.Our results revealed that the surface (hydragric horizon) and plough pan consistently exhibited higher soil OC content, dominated by the POC fraction. This dominance was negatively correlated with soil pH and positively correlated with silt+clay content. The plough pan effectively decoupled surface soil OC dynamics from those in the subsoil. Beneath the plough pan, soil OC content decreased, and the proportional contributions of soil OC functional pools diverged significantly according to parent material. Soils derived from alluvial deposits maintained relatively higher subsoil soil OC, with MAOC constituting a significantly larger fraction, a pattern strongly linked to Ca-OC complexation. In contrast, in soils derived from glaciofluvial deposits and Chengdu clay, the contribution of POC became more prominent in the subsoil, showing a negative correlation with pH but a positive correlation with free manganese oxides.Our findings reveal that the geochemical legacy of parent material dictates soil OC stabilization pathways. Accounting for this inherent control can significantly refine carbon accounting models and inform targeted.

# Effects of silicon modified biochar with different pyrolysis temperatures on carbon stabilization pathways in saline alkali soil

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**ABSTRACT**

Soil organic carbon (SOC) stabilization in saline-alkali soils is constrained by poor aggregate structure. This study investigated how biochar and Si-modified biochar produced at different pyrolysis temperatures (300℃, 500℃ and 700℃) influence carbon stability in Yellow River Delta saline-alkali soils through 120-day incubation experiments. Both types of biochar significantly improved soil properties and aggregate stability. Si-modified biochars exhibited superior mineral-associated organic carbon (MAOC) accumulation, with SiBC700 achieving the highest MAOC content. Lower pyrolysis temperatures (300-500℃) proved more effective for total carbon sequestration, with SiBC300 demonstrating the most effective aggregate formation. Partial least squares path modeling revealed aggregate stability as the strongest driver of SOC stability. These findings indicate that low-temperature Si-modified biochar optimizes aggregate-mediated carbon protection, while high-temperature variants enhance long-term mineral-associated carbon stabilization in saline-alkali soils.

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# Microbial mediation of deep soil inorganic carbon accumulation under long-term straw return in alkaline agricultural soils

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## ABSTRACT

Soil carbon sequestration is critical for climate change mitigation, especially in alkaline soils where inorganic carbon dominates below 1 m depth, which remains poorly understood. While straw return is known to enhance soil organic carbon, its long-term effects on deep soil inorganic carbon dynamics have been largely overlooked. This study employed a 12-year field experiment comparing straw return versus removal in a wheat-maize system, combined with carbon stock measurements across the 0-200 cm profile. We combined natural $^{13}C$ abundance analysis with laboratory incubation experiments using $^{13}C$-labeled glucose to trace carbon sources and quantify the fate of exogenous carbon in deep soil layers. Our results show that straw return significantly increased soil inorganic carbon stocks by 57.6 t $ha^{-1}$ in the 100-200 cm layers. Natural $^{13}C$ abundance data revealed that pedogenic carbon increased dramatically by 96.6% in topsoil (0-20 cm) and by 97.7% in deep soil (120-140 cm) ($P < 0.01$), whereas lithogenic carbon remained stable, indicating that soil inorganic carbon gains primarily originated from pedogenic carbonate formation. The $^{13}C$-labeled glucose incubation further demonstrated that 72.23% of the added $^{13}C$ was mineralized to $CO_2$, while 17.27% was transformed into soil inorganic carbon, suggesting that exogenous carbon entering the 120-140 cm soil layer enhances pedogenic carbonate formation. These findings reveal a previously overlooked, microbially mediated mechanism underlying deep soil inorganic carbon formation driven by straw-derived carbon inputs. Long-term straw return enhances surface organic carbon and deep soil inorganic carbon, offering a scalable, nature-based strategy to boost soil carbon storage in alkaline croplands.

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# Sewage Sludge Biochar Is Less Persistent Than Plant-Based Biochars in Soil

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**ABSTRACT**

Pyrolysis of sewage sludge into biochar has been proposed a strategy to stabilize organic carbon and mitigate environmental risks, yet the persistence of sludge-derived biochar C in soil remains poorly understood. Here we investigated the stability of biochar produced from sewage sludge collected from three wastewater treatment plants using a one-year laboratory incubation in soil. Sludge biochars retained 95–96% of added C after one year and were approximately seven times more recalcitrant than their feedstock. However, based on our conservative estimates, the median mean residence time (MRT, 27 years) was roughly an order of magnitude lower than that of plant-derived biochars recalculated from published datasets under comparable conditions (median 210 years). In addition, sludge biochar usually contains a large ash fraction and the abiotic CO2 release at the early stage of incubation may lead to underestimation of biochar persistence in soil. Carbonate removal had only a marginal effect on MRT estimates, likely because carbonate-derived CO2 was released slowly and carbonates were chemically protected within the biochar matrix. The reduction of biomass during pyrolysis led to an increase in concentrations of most trace elements with an exception for Hg. Overall, these results indicates that, relative to plant-derived biochars, the potential of using sewage sludge biochars for long-term soil C sequestration may be limited. Nonetheless, sludge biochar may still provide benefits for waste management and nutrient recycling, which requires further evaluation through life-cycle assessments and agronomic studies.

**Acknowledgments**

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# Application of Clay and Iron Oxide-Amended Compost: Linking Emission Reductions to Enhanced Soil Aggregation, Necromass, and Plant Performance

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**ABSTRACT**

Background: Farmers use composting since millennia to process organic waste into valuable organic soil amendments. During the composting process, more than 50 % of the carbon (C) is mineralized to $CO_2$ and more than 30 % of the nitrogen (N) is lost as $NH_3$ and $N_2O$. This C and N is thereby no longer available to form mineral associate organic matter (MAOM). The composting process is therefore the ideal starting point to mitigate these emissions to improve the sustainability of agricultural practices.

In our approach, we seek to decrease these losses by adding minerals directly to the start ofthe composting process, thereby providing both organic matter and reactive mineral surfaces upon application to promote microbial necromass build-up and C protection through organo- mineral associations and aggregation.

Objective: We compare abundant clay-rich waste with clay minerals and iron oxides, and linking gaseous emissions during the composting process to gaseous emission during the incubation with soil. At the same time, we research the effects of our engineered compost on plant performance and soil quality.

We hypothesize that mineral compost amendments decrease the C and N loss during the composting process , and compost amended with minerals increases soil aggregation, necromass build-up and stimulates plant performance.

Methods: For our mesocosm experiment, we mixed compost feedstock with 25 % (w/w) minerals (i.e., synthetic Goethite, volcanic Bentonite and natural clay) at the beginning of the composting process. 5 L mesocosms (n = 6 per treatment) were incubated for 40 days, with daily measurements of gaseous emissions ($CO_2$, $N_2O$, $CH_4$, $NH_3$). Additionally, every week, we monitored compost quality and maturity.

The resulting compost is transferred to a soil incubation experiment, during which gas measurements, soil quality and plant performance are assessed over period of 90 days.

Results: In preliminary experiments, we measured 20 % lower $CO_2$ emissions and 50 % higher $N_2O$ emissions in treatments with Bentonite compared to unamended compost. We will validate these results with our ongoing experiment where we test more treatments and different mineral amendments over a longer time.

Additionally, our set up allows us to examine if lower emissions during composting also translate to lower emissions over 90 d soil incubation and track their effects on soil quality and plant performance.

Conclusions: Our engineered compost approach seeks to demonstrate a strategy for increases C stabilization and decreased greenhouse gas emissions at the mesocosm scale. We show the potential to reduce C and N losses and at the same time maintain a productive soil that transforms organic matter into MAOM.

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# The Interaction between Mineral Transformation and Mineral-Associated Organic Matter (MAOM) Degradation

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**ABSTRACT**

Soil minerals, particularly high-surface-area secondary minerals like iron oxides, stabilize soil organic carbon (SOC). However, as these minerals transform into more crystalline forms over time, their ability to protect mineral-associated organic matter (MAOM) may also change, which is a dynamic feedback that is still not well understood. This study examines how ferrihydrite, a short-range-ordered iron oxide, protects polygalacturonic acid (PGA) under varying carbon loadings (C/Fe ratios) and Fe(II)-induced redox conditions.

We show that ferrihydrite transforms into goethite in pure mineral systems, diminishing its carbon protection potential due to reduced surface area. However, in mineral-PGA complexes, protection is maintained across different carbon saturation levels via distinct mechanisms. Under high carbon loading, PGA inhibits mineral transformation, forming stable complexes that in turn protect the PGA from degradation. Under low carbon loading, transformation proceeds but protection is maintained through relatively sufficient residual surface area. Notably, the degradation product galacturonic acid (GA) more effectively inhibits mineral transformation than PGA itself, creating a negative feedback that further stabilizes remaining organic matter.

Our findings demonstrate that carbon saturation governs two functional pathways in mineral–organic systems: a transformation-resistant pathway under high saturation and a surface-mediated protective pathway under low saturation. This updated conceptual model explains how MAOM can remain stable despite dynamic soil environment, and identifies soil carbon saturation as a key predictor of the stabilization mechanism. This work also presents SOC acts not as a passive substrate, but as an active regulator of mineral evolution and its own long-term persistence, offering insights for predicting SOC stability under environmental change.

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# Rapid versus delayed stabilization of residue-derived carbon by amorphous aluminum hydroxide and rice-husk biochar in alkaline soils

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**ABSTRACT**

Increasing soil organic carbon (SOC) levels is essential for sustainable agricultural productivity and climate change mitigation, particularly in alkaline soils with inherently low SOC. While amorphous Al hydroxide (Am-Al) significantly influences SOC stabilization in volcanic and humid-region soils, and biochar enhances SOC in temperate and tropical regions, their effectiveness and stabilization mechanisms in alkaline soils require further exploration. We conducted a 1-year incubation of low SOC alkaline soils (5.2 g $kg^{-1}$) amended with $^{13}C$-labeled maize residue (1 g $kg^{-1}$), with or without Am-Al or rice-husk biochar (each 10 g $kg^{-1}$); residue mineralization/retention was quantified and molecular composition profiled by solid-state $^{13}C$ NMR and Py-GC/MS. Rapid decomposition of plant residue ceased around 12 weeks, while plant residue-derived C and native SOC decomposition continued throughout the incubation period. Am-Al significantly reduced maize mineralization within the initial two weeks and retained 30% more residue-derived C than the control soil with maize addition after one year. $^{13}C$ NMR and pyrolysis–GC/MS showed smaller decreases in carbohydrate-C and saccharides and a higher carbon pReferences index and odd-even predominance of alkanes, indicating that Am-Al better preserved carbohydrate- and cuticular-wax-derived components, proxies for less-degraded residues. Respiration dynamics and molecular fingerprints indicate Am-Al rapidly stabilizes labile plant compounds, possibly through non-electrostatic sorption and ligand-exchange. Biochar increased residue-derived C retention by ~17%, but its effects on mineralization emerged later in the incubation (>6 months). We attribute this lag to surface degradation/activation of the biochar that then more efficiently stabilizes microbially processed compounds. Overall, adding Am-Al or biochar with plant residues significantly increased residue-derived C retention through immediate and delayed mechanisms, respectively. Treatments combining Am-Al or biochar with plant residue yielded a net positive C balance over the incubation, whereas residue alone did not. Thus, the application of Am-Al and biochar with plant residues represents a promising strategy for sustained C stabilization, thereby improving SOC in degraded alkaline soils.

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# Soil Erosion and Organic Matter Stabilization Mechanisms

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**ABSTRACT**

Erosion induces the transport and spatial redistribution of soil organic matter (SOM). The erosion-driven lateral transport of carbon-rich topsoil facilitates the movement of organic carbon along hillslopes, resulting in the exposure of subsurface soils and the effective burial of soil, sediments, and their associated protected organic carbon at depositional sites. Erosion processes influence the stability of SOM across various landscape positions along slopes. Currently, the three primary mechanisms by which erosion governs SOM stabilization include: (1) physical protection of soil organic carbon (SOC), involving the physical occlusion of SOC within aggregates or the spatial isolation of SOC from decomposers; (2) chemical interactions between organic carbon molecules and soil mineral surfaces; and (3) the chemical composition and molecular structure of SOM. Investigating the impact of soil erosion on the spatial heterogeneity of SOC is crucial for deepening our understanding of the interactions between geomorphic and biogeochemical processes.

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# Iron-Mediated Carbon Dynamics in Coastal Wetlands under Seawater Intrusion

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**ABSTRACT**

Coastal wetlands are critical global carbon reservoirs. Under climate change, seawater intrusion driven by sea-level rise poses a major threat to these ecosystems by increasing inundation frequency and duration and introducing large quantities of saline ions, thereby altering mineral–organic carbon (OC) interactions. However, the response of mineral-mediated OC preservation to seawater intrusion remains poorly understood.

To address this knowledge gap, we conducted a one-year laboratory incubation experiment using soils collected from 32 coastal wetlands across China. A simulation system encompassing a wide range of redox conditions and salinity gradients was established. The results showed that under prolonged anaerobic conditions, most reactive iron oxides were vulnerable to rapid reductive dissolution, resulting in an approximately 50% decline in iron-bound OC. This substantially weakened the capacity of iron minerals to stabilize OC and consequently enhanced the leaching loss of dissolved organic carbon (DOC). In addition, iron reduction accounted for 57% of anaerobic $CO_2$ production, representing the dominant pathway of anaerobic OC mineralization and partially offsetting the suppressive effect of anoxic conditions on OC decomposition. These findings indicate a functional shift of iron in coastal wetlands from a “rusty carbon sink” to a net carbon source.

With increasing salinity, the iron-reducing bacterial community exhibited a successional transition from *Clostridium* toward salt-tolerant genera, such as *Geothermobacter*. Even at salinities up to 30‰, iron reduction and associated $CO_2$ emissions were only marginally inhibited (<10%). In contrast, $CH_4$ emissions and the abundance of key methanogens declined sharply, primarily due to sulfate inhibition. Additionally, DOC leaching losses were substantially reduced under high-salinity conditions. Together, these results provide a mechanistic foundation for predicting the dynamic evolution of carbon pools in coastal wetlands under increasing seawater intrusion.

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# How no-tillage and cropping systems shape soil organic carbon formation and stabilization over time: Evidence from a 16-year chronosequence

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**ABSTRACT**

Soil organic carbon (SOC) plays a vital role in climate change mitigation, global food security, and soil health sustainability. While conservation tillage, particularly no-tillage (NT), has been empirically proven to enhance SOC, the temporal dynamics of SOC formation pathways remain poorly quantified across different cropping systems. Samples were collected from the surface layer in a long-term NT experiment (since 2001) that included two treatments: a) NT with continuous maize (NTMM); b) NT with maize-soybean rotation (NTMS). Plant- and microbial-derived C were quantified using lignin phenols and amino sugars as biomarkers to assess SOC formation pathway. Rock-Eval (RE) thermal analysis was used to assess SOC stability. SOC reached a steady-state after 12 years under both NTMS and NTMM. Although cropping systems influenced the fungal/bacterial ratio, they did not significantly alter the total microbial-derived C contribution to SOC in the steady-state (since 2014). Plant-derived C increased substantially, reaching 4.68 times (NTMS) and 5.97 times (NTMM) initial levels after 15 years. Microbial-derived C dominated SOC formation, but plant-derived C contributed more to SOC accumulation. The increase of hydrogen index and residual C calculated from RE indicated that NT increased both the labile C pool that promoted crop growth and the stable C pool which benefited the long-term SOC sequestration. These findings shed light on the SOC formation and stabilization change in time series in no-tillage and provide a stepping stone for SOC sequestration mechanism under different cropping systems.

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# Quantifying Soil Organic Carbon Deficits with Dynamic Baselines and Attainable Scenarios Modeled from Legacy Data

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## ABSTRACT

Soil organic carbon (SOC) stocks vary through time and across land use, climate, and soil type, making large-scale modeling of current SOC (SOCcs) challenging. The attainable steady-state stock (SOCat), the practically achievable SOC level under optimal soil, climate, and management conditions, is also dynamic because several soil loss pathways impact biophysical factors that control maximum storage capacity and can shift SOCat. Robust methods are therefore needed to model and extrapolate both SOCcs and SOCat so that current deficits (SOCdef = SOCat – SOCcs) can be quantified as unrealized sequestration capacity. Most existing theoretical and data-driven approaches are limited by lack of empirical evidence and temporally rich datasets, making them less reliable for dynamic estimation of SOC References states from legacy data alone.

To overcome these limitations, we combined legacy SOC observations, time adjustment, and data-driven modeling to generate spatially explicit 2024 SOCcs projections at 250 m resolution for the contiguous United States. We then estimated SOCat by identifying the maximum SOC stock within a spatially constrained similarity matrix of projected SOCcs and, using both References layers, calculated location-specific SOCdef. The resulting maps reveal pronounced heterogeneity, with mean deficits average 3.46 kg $m^{-2}$ in croplands versus 3.1 kg $m^{-2}$ in grasslands and forests. Larger deficits cluster on historically cultivated Mollisols and Alfisols in the Midwest, although they are lower than anticipated, indicating that decades of cultivation have depleted both SOCcs and SOCat. Degraded grasslands show similarly reduced storage capacity, underscoring the need to recalibrate sequestration targets to today's lower steady states. By providing empirically based, regionally calibrated SOCcs-SOCat-SOCdef benchmarks, our framework offers actionable References points to align management incentives, climate-smart policy, and site-specific restoration efforts.

**Key words:** time-adjusted SOC projections, current SOC stocks, soil water dynamics, ensemble machine learning

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# Equilibrium levels for SOC stocks under different environmental regimes

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## ABSTRACT

Despite wide acceptance of the potential of soils to store carbon, the effectiveness of formal schemes for soil carbon sequestration such as emission trading schemes remains uncertain. Concerns include the non-permanence of sequestered carbon, high costs of verification and inconsistent information on attainable soil organic carbon (SOC) under differing land management. The concept of SOC equilibrium, where soils achieve new higher equilibrium levels of carbon under more sustainable land management, can promote confidence in projected long-term carbon stocks. We demonstrate broad soil SOC equilibrium levels across Australia under 48 unique environmental - land management regimes, comprising three climate classes, four soil groups and four vegetation cover classes. The dataset comprised 4325 points across Australia with SOC stocks to 30 cm, sourced from the Australia-wide SCaRP monitoring project, supplemented with further state government soil data.

Random forest machine learning modelling using only key variables (annual precipitation, annual maximum daily temperature, soil-lithology and MODIS total fractional vegetation cover) revealed moderate performance with 68% of variation explained and a Lin's concordance value of 0.77 in independent validation. Plotting of median SOC stocks for the 48 regimes (Figure 1) demonstrates broadly consistent trends with varying climatic, soil type and vegetation cover conditions, although some regimes lack data or have apparent anomalies. The lowest stocks (20 t/ha) are demonstrated for dry - highly siliceous soil - low vegetation cover (<60%) conditions; whilst the highest stocks (110 t/ha) are demonstrated for wet - mafic soils (fertile clay rich) - high vegetation cover (>88%) conditions. A broadly consistent and predictable pattern exists between these two end-points.

The plot demonstrates the increase in stocks that are expected when transitioning to a higher vegetation cover class in the same climate and soil class, i.e., at the same site. We propose that the SOC stocks demonstrated for each of the 48 environmental – vegetation cover regimes represent broad equilibrium conditions for these regimes over Australia. Landholders and policy makers can have confidence in the reliability of these long-term equilibrium trends and thus confidence in decisions to participate in carbon trading schemes based upon them.

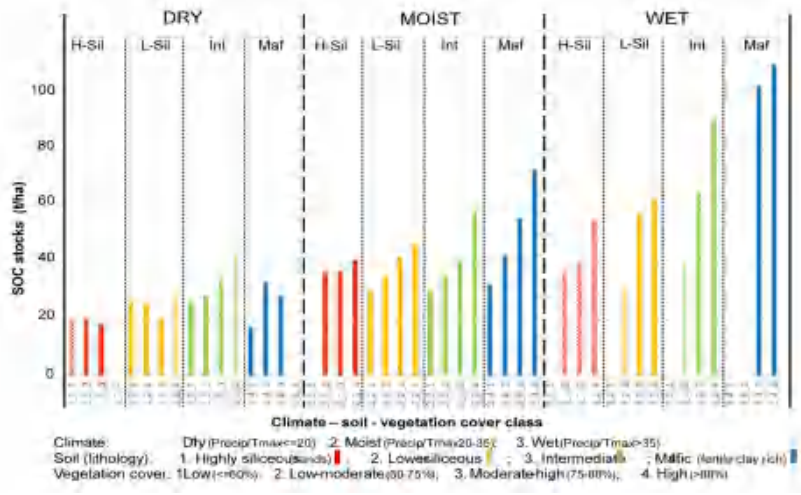



*Figure 1: Median SOC stocks by environmental – vegetation cover regime, Australia (0-30 cm, t/ha)*

# Microscale soil organic matter patches shaped by carbon- and nitrogen-rich microdomains

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**ABSTRACT**

Enhancing soil carbon storage through mineral-associated organic matter (OM) is widely advocated, yet the underlying storage mechanisms remain poorly understood. In soil systems, OM has been observed to be distributed heterogeneously in patches at the microbially relevant microscale. Due to the high spatial complexity of heterogeneous soil structures, data-driven approaches are required to quantify the spatial arrangement of OM. We elucidate patchy OM distribution patterns based on 450 measurements by nanoscale secondary ion mass spectrometry (NanoSIMS) with a field of view of 30x30 µm and 120 nm spatial resolution. To investigate general patterns of microspatial OM, we build a large dataset consisting of fine fractions (<20 µm) covering soils with diverse textures. The spatial patterns of OM distribution were analyzed at three different scales, each step zooming in more and more: the average coverage of OM patches was determined across several measurements per soil sample, the clustering of OM patches for each individual soil aggregate or particle, and the variation of C and N within the OM patches. Across various soil samples, microscale OM coverage on mineral surfaces was linearly correlated with the soil organic carbon content up to a coverage of 74% of the particle surface covered with OM at an OC content of 380 mg C g-1. When zooming into individual soil particles, the connectivity and clustering of OM patches revealed that higher OM coverage was related with a more clustered and connected pattern of OM patches. To evaluate the heterogeneity of C and N distribution within OM patches, we applied an advanced lacunarity analysis that incorporated a variance-driven h value and lacunarity curves derived from mean and variance metrics. Maximum change points in the lacunarity curve indicated pronounced spatial variation within OM patches. Patches were classified as heterogeneous when exhibiting both a second maximum change point on lacunarity curves and the detection of C-rich and N-rich microdomains, otherwise as homogeneous. The heterogeneous OM patches were significantly larger than the homogeneous OM patches, with a median size of 0.23 µm², regardless of the C or N composition. Heterogeneous OM patches size depends on the composite microdomains, large as C-rich microdomain (0.16 µm²) in C-dominated OM patches (7 µm²), or small as N-rich microdomain (0.08 µm²) in N dominated OM patches (1.10 µm²). These identified spatial C-rich and N-rich microdomains, which derived from distinct plant and microbial sources, form these mosaic-like OM patches over mineral surfaces. Micro spatial heterogeneity of OM determines microbial accessibility, mineral-organic protection mechanisms, and the formation of distinct biogeochemical microenvironments, providing essential insights for predicting soil carbon dynamics across scales.

**Keywords:** spatial heterogeneity, soil organic matter patches, NanoSIMS, functional microdomain

# Enrichment of metastable iron minerals in global coastal wetlands

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## ABSTRACT

Coastal wetlands represent a key reservoir of organic carbon (OC) at the land-ocean boundary, where interactions between iron (Fe) minerals and OC may influence long-term burial (Lalonde et al., 2012; Chen et al., 2024; Moore et al., 2023). Reactive, poorly crystalline and short-range-ordered Fe oxides are often proposed to protect OC, yet their expected vulnerability to reductive dissolution under anoxic conditions leaves their persistence and role in wetland soils uncertain. To evaluate these uncertainties, we integrated a global dataset of ~23,000 observations with a nationwide survey along China's coastline. Relative to uplands, coastal wetlands are enriched preferentially in poorly crystalline or short-range-ordered iron minerals over well-crystalline phases. Mössbauer spectroscopy confirms that ferrihydrite, nanogoethite, and highly disordered oxides dominate the Fe oxide pool in coastal wetland soils, while crystalline phases are minor, challenging the notion that reactive metastable minerals are removed preferentially under anoxic conditions. The abundance of reactive metastable Fe was most abundant in tropical wetlands, contrasting with tropical uplands where crystalline oxides are more prevalent. However, the proportion of total OC associated with Fe oxides is comparable between coastal wetlands (~13%) and uplands, despite the higher reactive Fe inventory in coastal wetlands. Furthermore, these widespread metastable iron minerals show no evidence of organic carbon saturation in coastal wetlands, highlighting potential for boosting this rusty carbon sink through management practices.

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# An approach to carbon credit finance feasibility assessment of SOC sequestration projects.

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**ABSTRACT**

Nature-based solutions (NBS) involving soil organic carbon (SOC) sequestration may be funded through the voluntary carbon market. However, such credits are issued upon verification procedure relating the sequestration achieved against the baseline assessment. Here we examine two project areas in South Africa and a virtual experiment:

1.Introduction of innovative soil cultivation methods and crop rotation into existing wheat production in the Western Cape province within a field trial conducted by the WC government department of agriculture from 2015 till 2025. The focus was on 0-5cm depth interval, where the most significant changes were expected in the no-till wheat production system. Here, the analysis was conducted using the statistical power of the baseline assessment, continuous yield monitoring and repeated soil sampling.

2. Restoration of degraded coastal thicket in the goat farming area of the Eastern Cape province. Here, the assessment was made for a 30cm fixed depth in stony soils. The method was based on the T-test of baseline sampling (degraded land) against the target values (closed canopy thicket) to optimize the cost/benefit function, where soil sampling and analysis are a significant part of the project implementation cost considering the study area of 10 000 ha with a view of expansion to 200 000 ha. The competing projects are aimed at restoration of 1 million ha of coastal thicket, and all the participants require a robust methodology for baseline assessment, monitoring and audit of SOC credits to compliment the credits generated by restoration of the vegetation.

3. In addition, virtual data sets were created and analyzed to optimize soil sampling and analysis depending on the basic statistics of the baseline and target values taking into consideration the magnitude of the expected intervention effect.

Recommendations are made regarding the calculation of the carbon credits, risk distribution between project participants as well as baseline establishment and adjustment of SOC monitoring time scales and audit frequency depending on the baseline and target statistics.

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# Straw return depth and tillage intensity drive changes in organic carbon fractions and their stability in black soil

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## ABSTRACT

Straw return is widely regarded as a promising management strategy to enhance soil organic carbon (SOC) stocks; however, the contents and stability of SOC fractions are jointly regulated by straw incorporation methods and tillage intensity. In this study, Fourier-transform infrared spectroscopy (FTIR), metabolomics, and biomarker analyses of amino sugars and lignin phenols were employed to characterize soil carbon fractions and their stability. Combined with microbial community profiling and metagenomic analysis, we further elucidated the dominant pathways of organic carbon turnover in rhizosphere and bulk soils. Specifically, compared with IT, the ST treatment significantly increased POC content and CBH activity in bulk soil and rhizosphere soil by 29.17% and 54.19%, respectively, while significantly decreasing the MAOC/POC ratio by 29.66%. Across all treatments, O-Alkyl C and Aromatic C=C/Alkyl-C in bulk soil showed a potential increasing trend. Relative to ST, IT significantly reduced the NOSC of bulk soil by 1.92% and increased the standard Gibbs free energy (ΔG°Cox) by 0.79%, suggesting that IT enhanced the stability of DOC in bulk soil. Furthermore, compared with IT, ST significantly upregulated the abundance of GH51, GH30, and GH26 genes in bulk and rhizosphere soils; these glycoside hydrolases are involved in the degradation of cellulose and hemicellulose. Collectively, low-disturbance ST rapidly increased POC accumulation, whereas IT was more conducive to enhancing organic carbon stability. Overall, this study provides theoretical support for sustainable agricultural management aimed at strengthening soil carbon sequestration through improved retention of carbon fractions.

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# Long-term field trials as a tool to evaluate the potential of fertilizers to maintain soil carbon persistence

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**ABSTRACT**

Realistic estimation of carbon storage in agricultural soils requires long-term field experiments, as the stability of soil organic carbon (SOC) under climate change is strongly influenced by fertilization strategies. We evaluated SOC dynamics in a long-term fertilization trial established in 1902 in central Germany. Over 120 years, combined mineral and organic fertilization increased SOC by 11–34% relative to the unfertilized control. Carbon accumulation slowed down and even turned to C losses after 80–95 years depending on fertilization strategy. We will discuss a potential of mineral and organic fertilization to mitigate the consequences of global warming and maintain long-term SOC stocks.

# Coupling of microbial carbon and energy fluxes in soil

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**ABSTRACT**

Microorganisms acquire both carbon (C) and energy required for growth and maintenance from the decomposition of organic substrates in soil. These matter and energy fluxes are tightly coupled according to stoichiometric relationships and the laws of thermodynamics, and unraveling the details of this coupling is essential for our understanding of soil functions mediated by microbes such as nutrient cycling and carbon storage. Recently, the ratio of heat release to $CO_2$ release during the microbial decomposition of organic compounds, the so-called Calorespirometric Ratio (CR), has received renewed attention as a useful tool for study of the bioenergetics of microbial growth in soils (Endress et al., 2024a, b). However, due to the complex and obscure nature of the soil system, measured CR values always require mechanistic models of the underlying processes for proper interpretation. In our study we show how with the help of simple dynamic bioenergetic models the linkage between apparent carbon use efficiency (CUE) and calorespirometric ratio (CR) can be formulated. Maintenance metabolism reduces apparent CUE, while its effects on CR depends on the energy content of the soil organic matter (SOM) or biomass compounds consumed to fuel maintenance. In arable soils, we find a close linear relationship between maintenance CR and average SOM energy content, while there is no clear pattern in forest soils.

**Acknowledgments**

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# Enhancing soil carbon sequestration and straw utilization through optimized microbial decomposition strategies

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**ABSTRACT**

Straw retention—through direct incorporation or composting—has emerged as a promising agricultural practice to enhance soil productivity and optimize straw resource utilization. To address the challenge of slow straw degradation, this study constructed high-efficiency microbial consortia for rapid straw decomposition and investigated their functional mechanisms.Straw-degrading strains were isolated from straw, soil, and compost samples, followed by evaluation of their carboxymethyl cellulase activity, filter paper disintegration capacity, and straw degradation efficiency. Two specialized microbial consortia were constructed based on temperature adaptation: a low-temperature resistant consortium (LRC) for direct straw incorporation and a high-temperature composting consortium (HCC) for enhanced decomposition under thermophilic conditions. For the LRC, a field experiment was designed with two tillage methods (straw mulching and deep tillage), and three treatments (non-microbial consortium, with microbial consortium, and without straw retention). Deep tillage with straw returning enhanced subsoil carbon sequestration and facilitated homogenization of microbial functions and communities across soil depths, potentially enhancing soil carbon capture and storage. In addition, applying the decomposition microbial consortium could improve the straw decomposition rate and increase SOC storage. For the HCC, three composting treatments were designed, including the treatment using only cattle manure (CK), the treatment mixing cattle manure and maize straw (CS), the treatment involving cattle manure, straw, and microbial consortium (CSM). The results showed that straw additives improved the formation of a diverse aerobic bacterial community and a unitary thermophilic fungal community, and promoted a stronger relationship between the bacterial and fungal communities.Furthermore, the CSM treatment could effectively increase the composting temperature, and improve the quality of the composting products. This study aimed to provide a critical basis and References for optimizing straw retention techniques and enhancing soil carbon sequestration capacity, thereby promoting sustainable agricultural development.

# Latitude-dependent temperature thresholds reverse soil organic carbon losses in global Mollisol croplands

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**ABSTRACT**

Soil organic carbon (SOC) in Mollisol croplands plays a crucial role in sustaining agricultural yields and combating climate change. Nevertheless, its spatial and temporal variations in these areas are still not well characterized, especially in the context of global warming. We integrated 5,535 field soil samples with over 1 million Landsat images using a hybrid probability deep learning framework to produce high-resolution SOC stock maps for global Mollisol croplands from 1990 to 2020. Our results show a 5.59% decline in SOC stocks over the past three decades, characterized by pronounced spatial heterogeneity and clear latitudinal gradients. Climate—especially temperature—emerges as the primary driver of SOC variability and change, even in intensively managed agricultural systems. Notably, we identify a nonlinear threshold response: while warming initially accelerates SOC losses, gains emerge when the rate of temperature change exceeds 0.034 °C/yr. This threshold increases from high to low latitudes, consistent with the theory of ecosystem thermal adaptation. By 2050, more than 60% of Mollisol cropland is expected to exceed this threshold, indicating the emergence of warming-enabled carbon reversal zones. These findings challenge linear assumptions in soil–climate feedbacks and offer a spatially explicit basis for climate-resilient soil carbon management under future warming.

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# Field experiment reveals varied earthworm densities boost soil organic carbon more than they increase carbon dioxide emissions

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**ABSTRACT**

Earthworms play crucial roles in regulating soil organic carbon (SOC) and greenhouse gas emissions in forest soils. Laboratory studies have proven that they promote soil carbon dioxide ($CO_2$) emissions. However, the effects of earthworm activity on forest soil $CO_2$ emissions and organic carbon (C) have not yet been quantified in situ, and the impact of different earthworm densities remain unclear. In this study, we investigated how earthworm (*Pheretima guillelmi*) activity at three densities (no earthworms, original density, and double the original density) affected SOC, its labile fractions, C-related enzyme activities, and soil $CO_2$ emissions in a Moso bamboo (*Phyllostachys edulis*) forest ecosystem over a six-month field experiment. Our results showed that the original earthworm density resulted in a 23.4% increase in soil $CO_2$ emissions, while double the original earthworm density resulted in a 9.6% reduction in emissions compared to the original density. Additionally, earthworms at both densities significantly increased the concentration of SOC and its labile fractions. Notably, the increase in SOC density (SOCD, SOC stock per unit land area, kg C $ha^{-1}$) induced by earthworm activity far exceeded the increase in $CO_2$-C emissions. Specifically, the earthworms at double the original density led to an 8.8-fold increase in SOCD, while the original density resulted in a 3.7-fold increase. Furthermore, our findings identified dissolved organic C (DOC) as the most critical labile organic C fraction influencing soil $CO_2$ emissions associated with earthworm activity, while β-glucosidase (BG) was the most significant C-related enzyme affecting soil $CO_2$ emissions driven by earthworm activity. These results provide important insights into the role of earthworms in both $CO_2$ emissions and SOC accumulation in subtropical forests.

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# Impact of long-term tillage on the soil organic carbon storage and its composition in black soil

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**ABSTRACT**

Soil organic carbon (SOC) is essential for maintaining soil fertility and promoting sustainable agricultural development. This study investigates the impact of long-term tillage practices on soil organic carbon storage (SOCS) and its components in dryland farming areas of the thin black soil region, based on a 40-year tillage practices experiment. It compares the effects of different tillage practices (Conventional rotary and ridge tillage, CT; no-tillage, NT; subsoiling tillage, ST; moldboard plowing, MP) on SOCS, active organic carbon components, and microbial necromass carbon (MNC) content in the 0~40 cm soil layer. The results showed that, compared to CT, NT significantly increased SOCS, SOC, dissolved organic carbon (DOC), microbial biomass carbon (MBC), easily oxidizable organic carbon (EOC), and MNC content in the 0-20 cm soil layer. Both ST and MP significantly improved SOCS, SOC, and EOC content in 0-20 and 20-40 cm soil layers compared to CT and increased MBC content in the 20-40 cm soil layer. Additionally, MP treatment significantly improved DOC, particulate organic carbon, and MNC content in the 20-40 cm soil layer compared to other treatments. ST and MP significantly reduced the contribution rate of MNC to SOC in both soil layers compared to CT and NT treatments. Structural equation modeling revealed that enhancing the mean weight diameter of soil aggregates, field capacity, and total phosphorus content, along with increasing $\beta$-glucosidase, amylase, and lignin peroxidase activities, could promote MNC accumulation. MP treatment facilitates the uniform distribution of SOC, active organic carbon, and MNC in the 0-40 cm soil layer, which is more conducive to the fixation of SOC in farmland in the thin black soil region.

**Key words:** Conservation tillage; Labile organic carbon fractions; Soil amino sugar; Microbial necromass carbon; Enzyme activity

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# Soil Biogeochemical Models: Current Applications and Future Directions

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## ABSTRACT

Soil biogeochemical models are widely used to simulate and predict soil organic carbon (SOC) dynamics, incorporating physical, chemical, and biological processes. These models vary significantly in structure, input parameters, and initial conditions, leading to considerable uncertainty in predictive outcomes.

SOC models are broadly categorized into process-based models (e.g., RothC, CENTURY, DNDC, EPIC) and statistical regression models. Process-based models simulate soil property changes by representing specific processes, making them suitable for small- to medium-scale simulations. However, they require regional calibration, and some parameters are difficult to obtain, limiting their performance at larger scales.Recent advancements increasingly integrate microbial processes, such as microbial enzyme activities, dormancy, and necromass production, to enhance SOC turnover simulations.

Machine-learning models, a key example of statistical models, autonomously learn from complex nonlinear relationships without empirical parameters. With the evolution from traditional machine learning to deep learning, their capabilities have significantly improved. Neural networks and random forests are widely applied in agriculture, studying the impacts of management measures on soil environments and crop yields across spatial and temporal scales.

This report, based on the reporter's studies, provides an in-depth exploration of the performance and application methodologies of mainstream SOC prediction models in agricultural environments. It systematically analyzes and compares the advantages and limitations of three distinct model categories—simple process-based models, complex mechanistic models, and statistical models—across varying spatial and temporal scales. The analysis highlights how these models differ in their ability to capture SOC dynamics, from field-scale processes to broader regional patterns, while addressing challenges such as parameterization, data requirements, and computational efficiency.

Looking ahead, the report also examines the future trajectory of biogeochemical models, emphasizing emerging trends such as integration of microbial processes, advancements in machine learning for model calibration, and enhanced coupling with other technologies. Furthermore, it discusses the pivotal role these models are expected to play in agricultural production practices, including precision farming, carbon sequestration strategies, and climate-smart agriculture initiatives, ultimately contributing to more sustainable and resilient food systems.

# Stover incorporation enhances soil carbon sequestration by improving the hydrophobicity of humic acid and soil water repellency

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**ABSTRACT**

The hydrophobicity of humic acid (HA) refers to the repulsive ability between HA, a component of soil humus, and water molecules, as well as its tendency to bind to non-polar substances. The core of the HA molecule is a polycyclic aromatic hydrocarbon skeleton, to which a large number of long-chain alkyl and aliphatic carbon groups are attached, and these groups are the main source of hydrophobicity. Soil water repellency (SWR) is a property that reduces soil's affinity for water and keeps water on the soil surface, which is mainly induced by hydrophobic organic matter covering the surface of soil particles. The two most common methods for characterizing SWR are contact angle and water drop penetration time. Stover incorporation is a core measure to increase soil carbon input, but it has problems such as rapid carbon decomposition and loss after incorporation. Traditional studies on soil carbon sequestration have mostly focused on macro aspects such as soil organic carbon (SOC) content and physical protection of aggregates, or micro mechanisms such as individual microbial decomposition, lacking systematic correlation analysis of "micro molecules-soil functions-carbon sequestration". HA molecules with strong hydrophobicity are difficult for microorganisms to contact and degrade, and can remain in the soil for a long time in the form of recalcitrant organic carbon; moderate SWR slows down water infiltration, maintains the air-water balance in soil pores, promotes the slow decomposition of SOC, and reduces carbon loss. This study takes HA hydrophobicity and SWR as the entry points to study soil carbon sequestration, because the two can multi-dimensionally reveal the intrinsic mechanism of soil carbon sequestration after stover incorporation from the perspectives of soil chemical and physical properties, as well as micro molecular structure and soil functions. The results showed that compared with the no-stover treatment, continuous full-rate stover incorporation for 5 years promoted HA formation and increased HA hydrophobicity by 21%; SOC content increased by 9.8%, and maize yield increased by 23%. A further experiment on one-time stover incorporation for 10 years showed that compared with conventional tillage, in the 3rd year after incorporation, HA hydrophobicity and SWR increased by 10% and 122% respectively, and SOC content increased by 24.1%. However, this effect began to weaken after 3 years and completely disappeared after 7 years. Stover incorporation enhances soil carbon sequestration capacity by regulating HA hydrophobicity and SWR, which is a suitable measure that balances carbon sequestration and crop yield increase. By demonstrating the relationship between HA hydrophobicity, SWR and SOC under specific conditions, this study provides a new perspective for observing soil carbon sequestration capacity.

**Acknowledgments**

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# Crop diversity enhances soil total carbon via increasing inorganic carbon concentration

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**ABSTRACT**

Numerous studies have demonstrated that increasing crop diversity can significantly enhance soil organic carbon (SOC) sequestration; however, its effects on soil inorganic carbon (SIC) remain poorly understood. At present, we evaluated the effects of maize/faba bean intercropping, N application rates, and inoculation rhizobia of faba bean on SIC in the top 20 cm of soil depth using a 13-year crop diversity field experiment.

The results showed that long-term faba bean/maize intercropping significantly increased soil total carbon (TC) concentration by 5.9 % and 7.0 % compared to faba bean monoculture and maize monoculture, respectively. Intercropping increased pedogenic carbonates (PIC) by 36.7%, thereby increasing SIC by 8.9% compared with faba bean monoculture. In addition, intercropping alleviated lithogenic carbonates (LIC) dissolution by 17.5%, which contributed to a 7.6% higher SIC content relative to maize monoculture. The formation of PIC was closely associated with increased concentrations of exchangeable $Ca^{2+}$ in soil, whereas the preservation of LIC was related to changes in SOC derived from $C_4$ crops and exchangeable $Mg^{2+}$ concentrations. In addition, inoculation of faba bean with rhizobia led to a decrease in soil pH, which consequently resulted in a reduction in soil inorganic carbon content.

Overall, our findings indicate that increasing crop diversity not only enhances SOC sequestration but also promotes total soil carbon sequestration by increasing SIC concentration. Our study highlights the importance of considering changes in inorganic carbon in the soil for accurately assessing the carbon sequestration potential of agricultural management practices. This study provides a theoretical basis for improving soil carbon sequestration and promoting sustainable agricultural development.

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# Estimating sequestration potentials of soil organic carbon in Black Soils of Northeast China

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**ABSTRACT**

Black soils (Chernozem, WRB) in China, very fertile due to its high SOC content and crop productivity, are distributed primarily in the northeast region of China, which is one of the three largest black soils area in the world. It is the most important soil resources and plays a critical role in ensuring food security in China. Carbon (C) sequestration on farmland ecosystem is of great importance in the terrestrial C cycle. Increasing soil organic C (SOC) sequestration not only will helpfully mitigate atmospheric $CO_2$, but also improve soil quality and ensure regional food security. It is well known that high soil fertility in agriculture is the improvement target pursued for the medium and low fertility soils in that it has the higher nutrients and the greater sequestration potentials of soil organic carbon (SOC). Based on this, we put forward that the cropland SOC content of high soil fertility would be the greatest and relative stable at the current conditions of agricultural management, soil properties and natural environment in the continuous cropping system, which was regarded as the SOC balance point (SOCb). The SOC sequestration potential (SOCsp) was the amount of SOC at the SOCb state. Afterwards, a SOCb statistical model ($R^2$=0.85) in the Chinese black soil dryland region was built using 52 topsoil samples (0-20cm) of high soil fertility with a model verification by other 23 high fertility samples, driven by the factors of annual mean temperature, annual precipitation, annual effective accumulative temperature, the ratio of precipitation and temperature, soil clay content and pH. The regional mean SOCb was estimated by 39.98 g/kg, and the regional mean SOCsp and the regional largest SOC storage would be 8.97 kg/m$^2$ and 522.92 Tg, respectively. The sensitivity analysis of this model showed that the high SOCb area distributed in the areas with low temperature, dry, high clay content and low pH, while the low SOCb area distributed in the areas with high temperature, wet, low soil clay content and high pH. Moreover, the means of regional SOC content in medium and low soil fertility levels could be increased by 13.17 g/kg and 23.98 g/kg between SOCb and them, respectively. As well, the means of increased regional SOC density in medium and low soil fertility levels could be 2.30 kg/m$^2$ and 4.57 kg/m$^2$ between SOCsp and them, respectively. Furthermore, the means of increased regional SOC storage in medium and low soil fertility levels could be 153.07 kg/m$^2$ and 252.35 kg/m$^2$ between the regional largest SOC storage and them, respectively. The study would give an important support to estimating regional SOC sequestration potential from the view of the differences of cropland soil fertility levels in order to more reasonably guide the current soil fertility improvement.

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# How Spatial Resolution Shapes Soil Carbon Estimates

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**ABSTRACT**

Understanding the influence of spatial resolution on geographical calculations is critical for accurately interpreting soil data and optimizing sampling strategies in agronomic and environmental studies, such as estimating field-scale carbon stocks. This study examines the impact of variations in data resolution, achieved through adjustments in observation density and spatial modeling of unsampled locations, on both the estimated field-scale organic carbon and its associated uncertainties. We utilized a synthetic spatial dataset, derived from 143 real-world observations, to serve as a geographic field with known values for all locations. This hypothetical field with known organic carbon stock values at each point (0–30 cm depth) served as the "ground truth." From this baseline, we applied multiple sampling designs and densities to compare calculated carbon stocks and their uncertainties with one another. Additionally, we tested the effect of spatial modeling to generate finer-resolution estimates with fewer direct observations. Results indicate that coarser resolutions consistently reduce apparent spatial variability while inflating uncertainty. Conversely, finer resolutions capture small-scale heterogeneity but require sufficient sampling density to avoid high prediction uncertainty. These findings demonstrate that variability in estimating field-level soil properties is influenced not only by measurement error but also by the choice of spatial resolution. Both estimated values and their uncertainties are resolution-dependent, raising the question of what level of certainty is necessary – in the context of measurement error - for confident carbon stock assessments in practical applications. This work provides a framework for identifying thresholds beyond which additional sampling yields diminishing returns under both direct measurement and spatial interpolation scenarios, offering guidance for researchers, practitioners, and policymakers who rely on spatial data analysis.

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# Development of Non-destructive Soil Bulk Density Measurement Technology for Efficient and Precise Estimation of Soil Carbon Stocks

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## ABSTRACT

Soil carbon sequestration is a key strategy for mitigating climate change, as soil is the largest terrestrial carbon sink. Quantifying Soil Organic Carbon (SOC) stocks requires accurate data on carbon concentration, bulk density, and gravel content. However, conventional bulk density measurement methods rely on destructive sampling, which is labor-intensive and time-consuming, especially given soil's high spatial heterogeneity. While hyperspectral imaging has advanced non-destructive carbon concentration estimation, non-destructive bulk density measurement methods remain limited. The thermal conductivity method, based on the simplified de-Vries model, offers a promising non-destructive alternative. However, models validated in laboratory settings often neglect in-situ heterogeneity, particularly gravel presence. This study aims to quantify the impact of gravel content on thermal conductivity-based bulk density estimation and refines the model for better field application. Experiments used 20 mL conical tubes to measure thermal conductivity under controlled conditions. Soil samples included three grassland soils (Sandy Loam, Silty Clay Loam, Loam) and one paddy soil (Sandy Loam). Gravel content was varied using 2–4 mm granite at weight ratios of 0, 0.1, and 0.2, and water content adjusted to 0, 0.1, and 0.2. A total of 108 measurements were taken with a TEMPOS thermal properties analyzer and SH-3 sensor. Results showed gravel significantly reduced the conventional model's accuracy. The model fit gravel-free soils reasonably well ($R^2$=0.735) but dropped sharply with gravel ($R^2$ : 0.488–0.530). To improve this, parameters ($\lambda_{soil}$ and $g_a$ (soil)) of the simplified de-Vries model were modified to include gravel as part of the soil matrix. The enhanced model showed better performance: $R^2$ increased from 0.571 to 0.602, and Standard Error (SE) decreased from 0.127 to 0.121. A rigorous 95% Confidence Interval (CI) evaluation confirmed robustness. Both models met the 1:1 correspondence condition, but the improved model had narrower CI widths for slope (0.316 to 0.301) and intercept (0.455 to 0.434), indicating greater precision and less uncertainty. This study quantified gravel's confounding effects and proposed a refined, more accurate model. Future work will extend to various lithogenic materials and consider in-situ factors like root biomass. This advancement is vital for integrating soil sensing with Physical AI, enabling real-time, high-resolution monitoring of soil carbon stocks to support global carbon management.

**Acknowledgments**

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# Parameters Optimization of RothC Model for Simulating Soil Organic Carbon Dynamics: A Case Study of Rice Straw and Soybean Residue Inputs

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**ABSTRACT**

Soil is one of the most potential carbon sinks globally, and accurate estimation of its organic carbon stock is crucial for enhancing carbon sequestration and developing effective climate change mitigation strategies. The Rothamsted Carbon Model (RothC) is a widely used tool for simulating soil carbon dynamics. It conceptualizes soil organic carbon (SOC) as five compartments: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM), and inert organic matter (IOM). The SOC variation is modeled through transfer rates among these compartments. Key input parameters, including climate data, plant residue carbon inputs, and the DPM/RPM ratio, strongly influence the model's performance and prediction accuracy. This study aimed to optimize the parameters related to plant carbon input and the DPM/RPM ratio in the RothC model to improve simulation accuracy. A long-term incubation experiment was conducted using three representative soil types (Lugang, Pingzhen, and Dapaisha), three temperature regimes (15, 25, and 35 °C), three moisture conditions (flooded, field capacity, and 60% of field capacity), three residue treatments (no residue, rice straw, or soybean residue at 1%, 2%, and 5%), and eight incubation periods (0.5, 1.5, 3, 6, 9, 12, 15, and 18 months). The estimation of the DPM/RPM ratio was based on SOC changes per unit time obtained from the incubation experiment. First, the decomposition rate of fresh organic matter ($k_1$) was derived from the initial carbon loss curves of each residue treatment. During the incubation process, when $k_1$ gradually reached a stable state, this stable phase was used to estimate the decomposition rate of the RPM fraction. The DPM and RPM proportions were then adjusted to control the relative contributions of the fast and slow decomposing pools. The optimal DPM/RPM ratios for soybean and rice residues were 1.44 and 0.75, respectively. The ratio for soybean was close to the default value for general crops in RothC. Adjusting the DPM/RPM ratio for rice residue to 0.75 reduced both the root mean square error (RMSE) and coefficient of variation (CV%), demonstrating that this adjustment effectively improved RothC's ability to simulate SOC dynamics in paddy soils. These findings provide essential parameterization References for future modeling of carbon sequestration in rice-based systems.

**Keywords:** RothC model; soil organic carbon; carbon input; DPM/RPM ratio; long-term incubation; parameter optimization; rice; soybean; carbon sequestration

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# An Integrated Framework Combining Spatial Soil Carbon Information and a Calibrated RothC Model for Improving Cropland SOC Estimation

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**ABSTRACT**

Cropland soil organic carbon (SOC) is recognized as an important carbon sink in national greenhouse gas inventories under the Land Use, Land-Use Change and Forestry (LULUCF) sector. However, the current IPCC Tier 1–2 soil carbon estimation methods are based on static coefficients and simplified equations, which limits their ability to adequately capture gradual soil carbon accumulation resulting from changes in soil management practices. In contrast, the results from Monitoring project on agri-environmental quality in Korea indicate a gradual increase in soil organic matter in croplands, highlighting the need for an advanced methodological framework that incorporates observation-based SOC dynamics into inventory estimation.

This study aims to improve cropland SOC sequestration estimation by proposing an integrated methodological approach that combines nationwide spatial SOC information with the Roth C model calibrated for domestic conditions. Nationwide cropland SOC maps were developed by integrating national soil testing program data with national soil survey data to establish spatial SOC baseline conditions. In addition, long-term organic matter amendment experiments were comprehensively analyzed to calibrate key Roth C model parameters for Korean cropland soils. This framework enables a more realistic simulation of SOC dynamics in response to soil management and organic matter inputs.

Overall, this study presents the applicability of a cropland SOC estimation methodology that reflects site-specific soil characteristics and long-term observational data, thereby providing an alternative to conventional coefficient-based approaches. The proposed framework is expected to serve as a methodological foundation for quantifying management-induced SOC sequestration in croplands and for advancing national greenhouse gas inventories toward IPCC Tier 3-level reporting.

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# Manure addition enhances straw-derived soil organic carbon formation and accrual by regulating microbial metabolism in paddy soils

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## ABSTRACT

Long-term application of straw and composted manure has received considerable attention for its enhancement of soil fertility and carbon sequestration. However, their combined application may provide even greater potential for soil organic carbon (SOC) formation and accrual. To elucidate the mechanisms underlying SOC accumulation under this practice and to inform nutrient management strategies, we collected paddy soils with low (10 g $kg^{-1}$) and high (20 g $kg^{-1}$) initial SOC levels. These soils were subjected to unfertilized control (CK), 10 t $ha^{-1}$ $^{13}C$-labeled straw returning (SS), composted manure with the same C content as 10 t $ha^{-1}$ straw returning (MM), 5 t $ha^{-1}$ $^{13}C$-labeled straw with composted manure with the same C content as 5 t $ha^{-1}$ straw returning (SM), and 10 t $ha^{-1}$ $^{13}C$-labeled straw with composted manure with the same C content as 10 t $ha^{-1}$ straw (SSMM), followed by indoor incubation for 30 and 150 d. Microbial metabolism and SOC contribution were assessed using $^{18}O$-$H_2O$ incubation and $^{13}C$ biomarker tracing techniques. Our results demonstrate that SOC accumulation was significantly enhanced under both low and high-C conditions with SSMM practice, and more effective in promoting straw-derived C contribution. Particulate OC contributed more to SOC accumulation than mineral-associated OC, significantly increased microbial diversity and the elevated of necromass C was primarily from bacterial necromass. Furthermore, microbial survival strategies shifted from K to r-strategists under combined treatment. Mechanistic modeling indicated that under low-C condition, SOC accumulation at SM was primarily driven by nutrient availability and microbial pathways, whereas at SSMM microbial community and metabolism became dominant roles. In contrast, under high-C condition, soil nutrient availability and microbial community structure directly promoted SOC accrual, while microbial metabolism exerted a negative effect—likely due to elevated microbial respiration and reduced C use efficiency, resulting in shorter C turnover times. In conclusion, the study highlights the critical role of composted manure in enhancing SOC contribution through its regulatory effects on nutrient availability and microbial metabolism functioning in paddy soils. These findings suggest that the optimal rates of combined organic amendments can significantly improve nutrient supply and straw-derived C sequestration in rice-based agro-ecosystems.

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# Using a historical a soil properties database (INFOSOLO) to analyse long-term variations in SOC, SOC fractions, and soil structure: a case study

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## ABSTRACT

Considering the pivotal influence soil organic carbon (SOC) on soil physical, chemical, and biological properties, it is considered a key indicator of soil health. Agriculture has globally reduced SOC, trough processes that are important to understand and reverse. This means that it is important to determine SOC variations over a timeframe that allows managers to adjust agricultural practices according to their actual impact. However, detecting SOC changes over short timeframes remains challenging, due to its characteristically slow rate of variation. Depending on the geographic location and the magnitude of SOC fluctuation, minimum sampling intervals of 10 to 20 years can be required to accurately detect changes.

Labile C fractions exhibit greater sensitivity to management practices, compared to total SOC, making them valuable early indicators of soil carbon dynamics. On the other hand, SOC plays a fundamental role in soil structure, by acting as a binding agent for stable aggregate development, which in turn protects SOC from microbial decomposition. Consequently, soil structure indicators have been recognized as effective short-term proxies for detecting SOC variations. In addition, SOC models can enhance the accuracy of SOC change estimates by incorporating critical variables, such as soil type, climate conditions, management practices, and baseline SOC concentrations.

In Portugal, the absence of a comprehensive soil health monitoring system and long-term experimental fields has constrained the investigation of SOC and other soil properties dynamics. Nevertheless, significant progress has been achieved through the development of INFOSOLO, a geoReferencesd open-access database containing nationwide soil property data collected since 1966. Furthermore, few studies have examined variations in SOC and labile SOC fractions under different management practices. no

The main objective of this work is to comprehensively assess SOC, SOC fractions, soil structure, and management practices, to develop a framework for detecting short-term SOC variations and projecting long-term changes, resulting from different management practices. To achieve this goal, a two-phase approach is necessary: (1) to identify sites with historical soil properties data (via INFOSOLO), where agricultural practices can be tracked, enabling analysis of long-term variations (>10 years) in SOC, SOC fractions, and soil structure across different management practices and pedo-climatic regions; and (2) to analyse correlations among SOC fractions, soil structure indicators, and management practices, combined with SOC modelling, to develop a robust framework for detecting short-term variations and inferring long-term trends. Preliminary results from a selected case study will be presented herein.

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# Dynamics and Stabilization Mechanisms of Organic Carbon Fractions in Engineering Waste Soil During Intensive Amendment

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## ABSTRACT

Engineering waste soils known as Anthrosols derived from subsoil typically possess an undeveloped structure and extremely low organic matter content. Rapid restoration via co-composting with organic wastes such as seafood sludge, manure, and straw has been demonstrated as an effective engineering approach for soil reconstruction. However, the dynamic evolution of soil organic carbon (SOC) fractions and their underlying stabilization mechanisms during this intensive process remain poorly understood. This study investigated the transformation processes of both labile and stable carbon pools, specifically focusing on the pivotal role of microbial necromass carbon (MNC) in driving carbon accumulation and stabilization.

A 17-day intensive amendment experiment was conducted using waste soils from a coastal engineering project in Yuhuan, China. By integrating physical fractionation of particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) with amino sugar biomarkers, we tracked the transition of sequestered carbon through three distinct evolutionary stages.

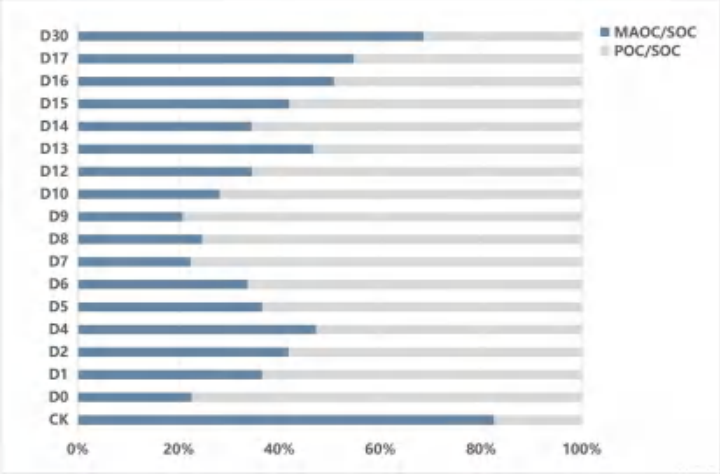



**Figure 1 Dynamics of the ratio of Mineral-associated Organic Carbon to Particulate Organic Carbon (MAOC/POC) during the 17-day co-composting process of engineering waste soil. CK represents the control group of raw waste soil without any organic amendments.**

The results revealed that the MAOC to POC ratio followed a characteristic decrease-increase-decrease trend, reflecting the complex biochemical responses of the soil system. In the initial stage from day 0 to day 4, the input of labile organic matter triggered a bacterial bloom. The rapid accumulation of unstable POC significantly outpaced the formation of MAOC. This led to a sharp decline in the MAOC to POC ratio and represented a state of carbon pool imbalance. In the second stage from day 4 to day 10, a successional shift toward fungal dominance was observed as indicated by the recovery of the fungal to bacterial residue ratio. This shift activated the microbial carbon pump (MCP), which facilitated the efficient conversion of exogenous carbon into MNC. Consequently, the MAOC to POC ratio rose significantly as MNC became the primary driver for MAOC accumulation. In the final stage from day 10 to the maturation of the nutrient soil, the ratio exhibited a slight decline as the system reached a state of re-equilibrium. This indicates that the carbon pool transitioned from violent fluctuation to a relatively stable dynamic balance during the maturation of the artificial soil.

In conclusion, this study demonstrates that microbial necromass plays a crucial role in the early-stage accumulation and stabilization of organic carbon in reconstructed engineering soils. The three-stage evolution of carbon fractions provides a mechanistic framework for optimizing waste soil formulations. These findings suggest that engineering waste soils can be transformed into stable carbon sinks within a remarkably short timeframe through microbial-mediated pathways.

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# The Carbon Sequestration Potential of Arable Soils in Russia Based on Dynamic Modeling

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## ABSTRACT

Carbon sequestration by arable soils is a key element of low-carbon development strategies. Improving the accuracy of assessing this potential is important for fulfilling Russia's climate policy objectives and transitioning to the third level of the IPCC methodology, which requires the use of national monitoring data.

Based on simulation modeling, the possibility of controlling carbon sequestration and the expected dynamics of organic C stocks in the arable layer of chernozems and sod-podzolic soils were assessed through the implementation of a set of carbon-saving technologies based on the RothC carbon model.

To increasing the detail of modeling a methodology for calculating net primary products based on national statistical data from the Russian Federation was developed and tested. Using data on crop yields and cultivated areas obtained at the municipal level, the biomass of plant residues and carbon input into the soil were calculated.

Refinement of estimates of carbon sequestration compared to the FAO GSOCseq project methodology shows an increase in the rate of sequestration by arable soils. Thus, for the Rostov Region, estimates based on global models that characterized the region as a weak carbon emitter (-0.007 t C·ha$^{-1}$·year$^{-1}$) changed when statistical data was used to show a small but steady accumulation (0.032 t C·ha$^{-1}$·year$^{-1}$) even with business as usual scenario. With the implementation of sustainable soil management scenarios, the sequestration potential could increase to 0.161 t C·ha$^{-1}$·year$^{-1}$, which makes the region one of the most promising ones for the introduction of carbon farming.

The possibility of achieving a carbon accumulation rate of 4 ppm in arable soils is demonstrated. Dynamic modeling of sequestration processes has significantly expanded the value of databases from long-term field experiments with fertilizers as sources of local data on the prospects for managing $CO_2$ sequestration and emissions in order to avoid possible losses of soil carbon and maximize the benefits provided by expected climate change. With high initial carbon stocks in arable chernozems, the role of organic fertilizer forms and rates in sequestration management increases. Under future climate conditions, the non-Chernozem zone is quite promising in terms of both the absolute values of soil carbon sequestration and the duration of this process.

**Acknowledgments**

The research was carried out as part of the most important innovative project of national importance "Development of a system for ground-based and remote monitoring of carbon pools and greenhouse gas fluxes in the territory of the Russian Federation, ensuring the creation of recording data systems on the fluxes of climate-active substances and the carbon budget in forests and other terrestrial ecological systems" (Registration number: 123030300031-6)."

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# Soil Carbon Sequestration: Realism versus Potential

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**ABSTRACT**

Climate change and food insecurity are the two major threats to humankind and both are linked to global cycling of C. Soil acts as a sink for both natural and anthropogenic $CO_2$ in short and long-term global C cycles. The main question is "Can soils act as a short and long-term sink to remove ever increasing amounts of $CO_2$ due to anthropogenic release of fossil C into the atmosphere". The short-term C cycle is dominated by biological processes of net primary production (NPP) and net secondary production (NSP). The long-term Cycle represents more permanent storage such as sedimentary rock. Soil organic carbon (SOC) is one of the most important characteristics of soils that result from the interplay of net primary producers, soil biomass and mineralogy. Decomposers particularly the soil microbial biomass are the main players of the NSP but are dependent NPP as a source of autotrophic C that they degrade into products that eventually stabilize into the soil matrix. The resulting soil organic matter is the foundation of ecosystems, providing the necessary resources to drive NPP. The stabilization of SOC with reactive minerals, particularly clays and short-range order and metal oxide minerals, provide a matrix that supports soil structure and function, increases moisture holding capacity and contains nutrients that allows net primary producers such as crops to thrive. The importance of SOC to support food and fiber production cannot be understated. Recent studies and in particular predictive efforts have supported the 4 per mil initiative (COP21) that suggests an increase in global SOC stocks by 4 per mille (or 0.4 %) per year or 3.6 to 4.3 Gt C is possible and could consume up to 40% of annual fossil C emissions. To meet this lofty goal, global soils on average would need to sequester 1.5Gt annually. Yields for major world grain crops (e.g., wheat, rice, maize) typically range from 4 to 8 metric tons per hectare (t/ha) with an equivalent amount of crop residue return. This means that 19 to 38% conversion of crop residue and root inputs into SOC. Some productive temperate climate areas may be able to achieve these yields goals, however lower producing areas such as arid climates will be lower requiring higher yielding areas to be more productive. These issues including cost and societal benefit will be covered to help in understanding the limits of C-sequestration in soils.

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# Dynamics of Soil Organic Carbon and Its Mineralization in Black Soils of Northeast China

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**ABSTRACT**

Black soils in Northeast China, classified as Isohumisols in Chinese Soil Taxonomy, are critical for national food security, contributing 25% of China's total grain output (64% soybean, 42% corn, 19% rice in 2022) and covering 18.53 million hectares across Heilongjiang, Jilin, Liaoning, and Inner Mongolia. Characterized by high soil organic carbon (SOC), total nitrogen, and clay content, these soils face severe threats of SOC loss and degradation. The study synthesizes dynamics of SOC and its mineralization processes, along with driving factors and mitigation strategies. Long-term monitoring (1980–2011) shows that Northeast China's black soils are the only region with declining SOC nationally: average loss of -0.41 Mg C $ha^{-1}$, compared to a national increase of 4.34 Mg C $ha^{-1}$. In Heilongjiang Province, ~85% of black soil areas exhibit SOC reduction, with Hailun (-19.1%), Baoqing (-11.2%), and Liandian (-0.49 Mg C $ha^{-1}$ $yr^{-1}$) being severely affected. Key drivers of SOC decline include intensive tillage, straw removal/burning, and climate warming. Across the geographic gradient of Northeast China's black soil region, fungal diversity and mineral protection enhance SOC accumulation via microbial necromass and mineral-associated organic carbon. Long-term full straw return with NPK fertilizer increases SOC by 14.2% (9.5‰ $yr^{-1}$) over 15 years, with maize-derived C contributing more than soybean. Regarding SOC mineralization, straw return induces a positive priming effect but reduces temperature sensitivity. Microbial biomass and nutrient availability regulate priming effect: higher microbial biomass promotes SOM-derived DOC/MBC production, while N addition suppresses priming effect. Environmental conditions (temperature/moisture) interact with SOC content, with the highest PE at 45% water-holding capacity and 22°C; drought dampens $Q_{10}$, supporting the carbon quality-temperature hypothesis. China has implemented national actions, including the National Black Soil Protection Project (2021–2025) and conservation tillage. Optimized agricultural management (organic input, conservation tillage, crop rotation) is vital to reverse SOC loss and sustain black soil fertility.

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# Driving Factors and Spatiotemporal Variations of Soil Organic Carbon in the Northeast China Plain

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## ABSTRACT

Soil organic carbon (SOC) plays a critical role in ensuring food security and addressing climate change. This study, based on a regional-scale soil quality geochemical monitoring network established by the China Geological Survey (covering approximately 2.6×10$^5$ km$^2$), systematically analyzed the spatiotemporal evolution characteristics and driving mechanisms of SOC in the Northeast China Plain. A total of 1910 and 1920 topsoil samples were collected in 2005 and 2018, respectively, and analyzed using empirical Bayesian kriging interpolation and random forest methods. The results indicate that: (1) SOC density ranged from 0.83 to 8.79 kg·C·m$^{-2}$ (median: 3.25 kg·C·m$^{-2}$). The spatial distribution of SOC exhibited significant zonal characteristics, with concentrations gradually increasing from the southwest to the northeast. Soil SiO2 content, Fe2O3 content, and mean annual precipitation were identified as the primary driving factors, explaining 38.2%, 18.8%, and 13.3% of the spatial variability, respectively, while other factors such as topography, NPP, and NDVI showed relatively weaker explanatory power. (2) From 2005 to 2018, SOC density and SOC stock increased by 0.16 kg·C·m$^{-2}$ and 49.79 Tg, respectively, representing growth rates of 5.18% and 5.84%. Spatially, 57.91% of the study area exhibited an increase in SOC, with 18.07% of the area showing a growth rate exceeding 20.00%. (3) Land use change had a limited contribution to SOC stock variation, as regions with unchanged land use types accounted for 73.03% of the total SOC stock increase. This study reveals the spatiotemporal evolution patterns of SOC in the Northeast China Plain, providing scientific insights for regional soil carbon management and offering important guidance for formulating effective soil conservation strategies.

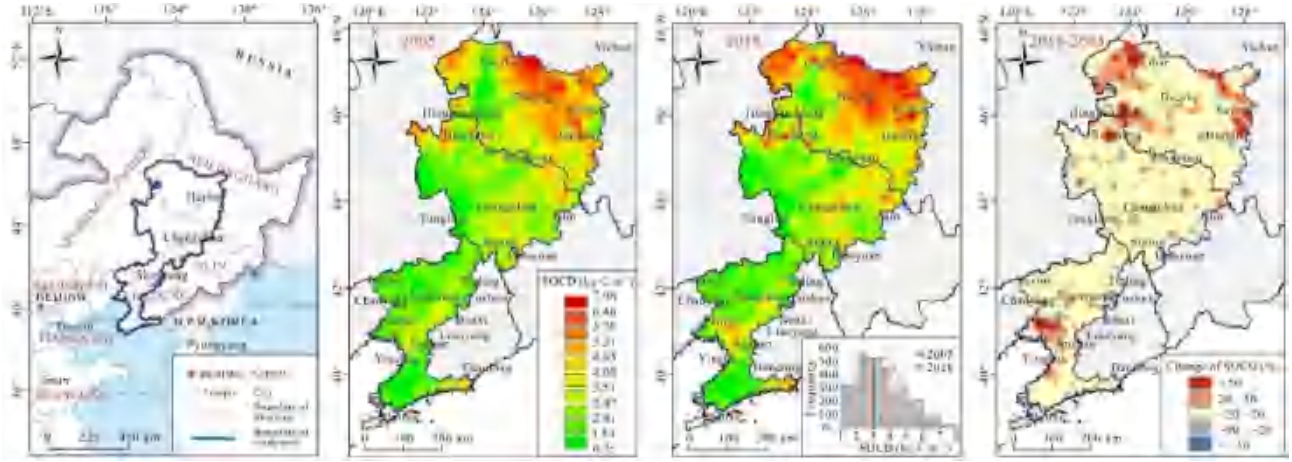


Fig 1. Spatial distribution of soil organic carbon density (SOCD) in 2005 and 2018, and SOCD changes (2018–

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# Cultivation Management Reshapes Soil Profile Configuration and Organic Carbon Sequestration: Evidence from a 45-Year Field Study

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## ABSTRACT

Long-term human cultivation activities are the key factors of the vertical distribution and storage dynamics of soil organic carbon (SOC) in cropland. Based on a 45-year long-term field experiment, this study systematically compared SOC dynamics and carbon storage characteristics in soil profiles (0–200 cm) between cultivated land and adjacent natural forest. The findings reveal the hierarchical regulatory effects of tillage management on the soil carbon pool.

The results show that: (1) Under both land use types, SOC content decreased exponentially with depth, but values in cultivated soils were 0.35–1.54% lower than in forest soils at each layer. SOC content in surface soil (0–78 cm) was significantly higher than in the subsoil (78–158 cm) and substratum layers (158–200 cm) ($p < 0.01$). At equivalent depths, SOC in cultivated land was significantly lower than in forest land ($p < 0.01$). Over 45 years, the SOC accumulation rate in the surface soil of cropland (0.07 $g \cdot kg^{-1} \cdot yr^{-1}$) was only half that of forest land (0.14 $g \cdot kg^{-1} \cdot yr^{-1}$). (2) The controls of soil physicochemical properties on SOC differed with land use: in forest soils, SOC correlated positively with clay content ($r = 0.63$, $p < 0.01$), whereas in cultivated soils, SOC was primarily regulated by total nitrogen ($r = 0.94$, $p < 0.01$) and sand content ($r = 0.60$, $p < 0.01$) and negatively correlated with bulk density ($r = -0.55$, $p < 0.01$) and pH value ($r = -0.45$, $p < 0.05$). (3) Long-term tillage significantly reshaped soil profile structure, thickening the plough layer from 20 cm to 78 cm. Surface carbon storage reached 20.76 $t \cdot ha^{-2}$, an increase of 11.13 $t \cdot ha^{-2}$ compared with forest soil ($p < 0.01$). However, storage decreased by 4.99 $t \cdot ha^{-2}$ and 7.60 $t \cdot ha^{-2}$ in the subsoil and substratum layers, respectively ($p < 0.01$). The SOC storage increment rate was 50.95 $t \cdot ha^{-2} \cdot yr^{-1}$ higher than that of forest soil in the surface layer but 46.81 $t \cdot ha^{-2} \cdot yr^{-1}$ and 11.12 $t \cdot ha^{-2} \cdot yr^{-1}$ lower in deeper layers. These results confirm that cultivation alters soil structure and material cycling, enhancing carbon enrichment in surface soils while accelerating depletion of deeper carbon pools. This provides new insights into the vertical differentiation mechanisms of SOC under long-term agricultural management.

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# Reconstructing rangeland soil carbon erosion using sediment trapped behind small reservoir dams

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## ABSTRACT

Human-induced soil erosion significantly impacts soil organic carbon (SOC) dynamics, particularly in rangelands, where land degradation and overgrazing exacerbate SOC loss. This study investigates whether sediments from small farm reservoirs in South Africa's Karoo rangelands can serve as archives to reconstruct the temporal pattern of SOC changes during the 20$^{th}$-century. Sediments from three dams, accumulated during different time periods, were analysed for radionuclide markers (e.g. $^{137}$Cs), organic carbon (OC) content, sediment yield and OC flux. The results illustrate the suitability of the farm dam sediments to reconstruct soil erosion history in the Karoo and reveal distinct temporal patterns of SOC erosion for each catchment. For all dams, increases in sediment input into the reservoirs did not correspond to a proportional increase in OC accumulation, highlighting the influence of land degradation on SOC depletion over time. Dam-specific variations underscore the role of land use and local heterogeneity in shaping erosion and carbon fluxes. These findings suggest that lateral SOC transfer has been dynamic during the 20$^{th}$ century, challenging models that assume constant sediment OC concentrations over time. Therefore, this study illustrates the importance of reconstructing past SOC dynamics and gain a correct understanding of the carbon fluxes in degraded rangelands and their broader implications for the global carbon cycle during the 20$^{th}$ century.

**Keywords:** soil carbon erosion; rangeland degradation; dam sediment; temporal pattern

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# Conservation tillage and wheat straw managements improve soil organic carbon sequestration via calcium-mediated microbial communities and aggregate stability in Calcaric Cambisols

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## ABSTRACT

Conservation tillage improves soil organic carbon (SOC) management by balancing microbial decomposition and physico-chemical protection. Minerals stabilize SOC, but how tillage practices affect calcium (Ca) speciation and its role in microbial–mineral–organic matter interactions in calcareous soils remains unclear. Thus, a 22-year tillage experiment and soil incubation were conducted to investigate Ca-mediated SOC sequestration and mineralization. Conservation tillage, including no-tillage with straw mulch (NTS) and subsoil tillage with straw mulch (STS), increased SOC storage by 9.9-14.3 % at 0-20 cm soil depth by promoting organo-Ca associations, compared to conventional tillage without straw return (CTN) and reduced tillage without straw return (RTN). Moreover, NTS and STS increased aggregate stability and macroaggregate proportion, reducing total SOC mineralization, as macroaggregates had lower SOC mineralization than microaggregates. In aggregates, increased exchangeable Ca was linked to higher particle- and mineral-associated SOC and lower SOC mineralization, showing positive ($p < 0.01$) and negative ($p < 0.001$) relationships, respectively. Compared to CTN and RTN, long-term NTS and STS not only promoted the transformation of $CaCO_3$ to exchangeable Ca, but also increased microbial biomass, especially the proportion of Gram-negative and arbuscular mycorrhizal fungi. Mechanistically, higher $Ca^{2+}$ reshaped bacterial communities and promoted the microbial by-product binding to the minerals to form stable organo-Ca complexes, which was supported by the positive correlations between $Ca^{2+}$, microbial composition and SOC content (PLS-PM, $p < 0.01$). Overall, conservation tillage increased Ca availability for carbon binding by mediating microbial structures, thereby promoting aggregate protection and SOC stability in Calcaric Cambisols.

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# Evaluating the Applicability of the RothC Model for Soil Organic Carbon Dynamics in Canadian Prairie Grasslands Using Physical Fractionation

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**ABSTRACT**

This project aims to validate and calibrate the Rothamsted Carbon Model (RothC) for Canadian prairie soils by integrating empirical data from physical fractionation with model-based simulations, following the framework of Zimmermann et al. (2007) and Jebari et al. (2021). 74 air-dried soil samples from Saskatchewan grasslands will undergo Zimmermann's multi-step fractionation to separate SOC into five identified pools and be connected to RothC simulation.

The empirical pool data will initialize three RothC configurations: (1) $RothC_0$—a baseline model using default initialization; (2) $RothC_2$—integrating plant residue and rhizodeposition and (3) $RothC_3$—a water-modified version incorporating decomposition constraints under saturated conditions. Monthly climatic data—temperature, precipitation, and potential evapotranspiration—from Environment and Climate Change Canada will be calculated.

In March 2026, follow-up soil sampling at the same sites will provide SOC data for short-term validation. Modeled SOC values from the three configurations will be compared to measured changes using Root Mean Square Error (RMSE) and Coefficient of Determination ($R^2$). Correlation analysis between measured SOC fractions and modeled pools, following Zimmermann's approach, will identify the most effective configuration for simulating short-term SOC dynamics in Canadian Prairie soils.

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# Mid-Infrared Spectroscopy for Soil Organic Carbon Estimation: Global Insights and Case Studies

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**ABSTRACT**

Soil organic carbon (SOC) plays a pivotal role in agricultural productivity, climate mitigation, and ecosystem stability. However, traditional chemical analysis methods for SOC quantification are costly, time-consuming, and environmentally intensive. This study employs mid-infrared (MIR) spectroscopy as a rapid, low-cost, and sustainable alternative for SOC estimation. A comprehensive meta-analysis of 176 peer-reviewed studies was conducted to assess the influence of soil sample preparation, spectral pretreatment, and chemometric modeling on MIR-based SOC prediction accuracy. The results reveal that finely ground samples and specific pretreatments such as multiplicative scatter correction (MSC*) and Savitzky–Golay derivative (SGD) significantly enhance model performance ($R^2$ up to 0.91, RMSE < 1.0). Optimal spectral parameters include the 4000–600 $cm^{-1}$ range, 4–8 $cm^{-1}$ resolution, and ≥64 scans per sample. Among chemometric techniques, partial least squares regression (PLSR) remains the most robust, though emerging methods like Cubist and machine learning models show promise. Validation using datasets from China, Kenya, Indonesia, and Australia confirms the model's adaptability and scalability. The Australian case study—covering 430 farms and 15,480 samples—demonstrates that MIR reduces analytical costs by more than half while maintaining high accuracy ($R^2$ = 0.87, RMSE = 16.9 t $ha^{-1}$). Overall, MIR spectroscopy offers a transformative pathway for efficient SOC monitoring, enabling climate-smart soil management and supporting national carbon accounting frameworks.

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# Enhancing spectral estimation accuracy of soil organic carbon by using geographic region and clay content as covariates

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**ABSTRACT**

Accurate monitoring of soil organic carbon (SOC) content, a core indicator of soil quality and ecosystem health, is important for sustainable agricultural development. Visible-near infrared (Vis-NIR) spectroscopy has become an important monitoring method owing to its fast, non-destructive, and cost-effective advantages. Regional soil data is difficult to cover soil attribute variations in complex environments. Soil spectral library (SSL) significantly enhances the comprehensiveness of data by integrating spectral and attribute data from multiple areas and types of soils. However, SSL has strong heterogeneity, and its soil samples may differ significantly in their attributes from the soil samples of the target area, which may lower the model accuracy. In this study, 210 soil samples were collected from three irrigated agricultural areas in Xinjiang, China, to construct a regional soil spectral library, and spectral preprocessing was combined with regression algorithms for modeling. Stratification modeling and covariate modeling strategies based on geographic region, soil type, clay content, and spectral type were proposed and evaluated. The results showed that the modeling based on first-order differential combined with random forest (FD-RF) showed optimal performance in all modeling strategies. Stratification modeling strategies and covariate modeling strategies significantly increased the SOC estimation accuracy compared with the entire dataset-based modeling. The geographic region-based stratification model ($R^2_v$ = 0.788) had a higher estimation accuracy than soil type-, clay content-, and spectral type-based stratification models ($R^2_v$ = 0.521–0.717), and the model synergizing spectral data with geographic region and clay content had optimal SOC estimation performance, with an $R^2_v$ of 0.871, which was 44.21 % higher than the entire dataset-based model. This study demonstrates that using geographic region and clay content as covariates for modeling can reduce the influence of soil spatial heterogeneity on SOC estimation accuracy, and provides a new strategy for spectral estimation of soil properties.

**Keywords:** Covariate; Modeling; Random forest; Soil spatial heterogeneity; Stratification; Visible-near infrared



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# Integration of Smartphone Imagery with Topographic Parameters for Soil Organic Carbon Prediction in the Indo-Gangetic Plains: An Interpretable Machine Learning Approach

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**ABSTRACT**

Accurate assessment of soil organic carbon (SOC) is crucial for sustainable agriculture and climate change mitigation; however, conventional laboratory methods remain expensive and time-consuming, particularly for smallholder farmers in developing countries. This study evaluated five machine learning models (Random Forest (RF), Artificial Neural Network (ANN), Support Vector Machine (SVM), Boosted Regression Tree (BRT), and eXtreme Gradient Boosting (XGBoost)) for SOC prediction across the Indo-Gangetic Plains using smartphone imagery and topographic parameters. Two hundred soil samples were collected from agricultural fields spanning Karnal and Kaithal districts of Haryana, IARI farm of Delhi, Varanasi district of Uttar Pradesh, and Nadia district of West Bengal, representing diverse agroecological conditions. Three modelling approaches were tested: Model-1 used smartphone images as sole predictors, showing poor performance with testing $R^2$ values of 0.005-0.06 and normalized root mean square error (nRMSE) of 0.31-0.34. SVM achieved best performance ($R^2$ = 0.06, nRMSE = 0.31). Model-2 employed topographic parameters derived from digital elevation models, including slope, aspect, openness measures, terrain ruggedness index, and total curvature. This approach outperformed Model-1, with RF achieving $R^2$ = 0.147 and nRMSE = 0.29. Model-3 integrated smartphone imagery with topographic features, producing exceptional results. XGBoost achieved optimal performance ($R^2$ = 0.717, nRMSE = 0.16, Nash-Sutcliffe efficiency = 0.710, concordance correlation coefficient = 0.82, d-index = 0.906), representing significant improvement over individual approaches. The integrated framework enables real-time soil assessment, eliminating expensive laboratory requirements and supporting resource-limited farmers in making informed management decisions.

**Keywords:** Soil organic carbon (SOC), Machine learning, Smartphone imagery, Topographic parameters Indo-Gangetic Plains

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# Differences in the physical protection mechanisms of soil organic carbon with 13C-labeled straw and biochar

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## ABSTRACT

Straw-derived biochar has a greater potential for carbon (C) sequestration than straw that is directly returned into the soils. An incubation experiment was carried out to explore the impact of different straw returning modes (straw and biochar) on soil organic C (SOC) sequestration and their underlying physical protection mechanisms. The $^{13}C$-labeled straw and biochar were applied at rates of 0.5% and 1% (w/w) to three typical upland soils collected from Yuzhong, Yangling, and Changwu (labeled as YZ, YL, and CW, respectively) on the Loess Plateau in China. Soil C fractions and isotopic C were measured, and the pore structure of macroaggregates was quantified using X-ray computed tomography (CT) and verified by 3D visualization images. Compared to the control (CK), the addition of straw biochar increased SOC contents more than straw in three soils, especially at higher rates. Only biochar improved particulate organic C (POC) contents, and the changes of mineral-associated organic C (MOC) contents differed with soil types. Soil potential C mineralization (PCM) and microbial biomass C (MBC) increased with the addition of straw rather than biochar, except for MBC in YZ soil. The contribution percentages and contents of $^{13}C$ in SOC, POC, and MOC were higher with biochar addition than with straw addition, especially in YZ and YL soils. The total porosity and pore connectivity increased with straw addition in YL soil and with the 1% biochar application in CW soil. However, only isolated porosity increased in YZ soil. Meanwhile, the macropores increased while the mesopores and micropores showed decreasing trends in both YL and CW soils. Additionally, YL soil exhibited more pronounced positive correlations between pore structure and C fractions compared to the other two soils. These findings suggested that the sequestration of SOC was attributed to the improvements of POC and MOC by affecting soil pore structure in straw- and biochar-amended soils, respectively. Therefore, both the form of imported C and soil properties, such as the fertility and pore structure, should be comprehensively considered to fully optimize the potential for C sequestration in farmland soils.

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# Recognizing and Reducing Effects of Moisture-Salt Coexistence on Soil Organic Matter Spectral Prediction:From Laboratory to Satellite

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## ABSTRACT

Soil organic matter (SOM) mapping in salinized areas is crucial for scientific guidance on soil salinization. However, accurately mapping SOM is challenging due to the intricate interplay between soil moisture content (SMC) and soil salt content (SSC), which significantly influences soil spectra. Unlike prior research that has separately examined the impacts of moisture or salinity, this study delves into the combined effects of these factors on SOM spectra. The objective of this study is to develop and validate several spectral optimization algorithms at both the laboratory and satellite levels. In October 2020, a study was conducted using 291 ground-truth data to examine the impact of various moisture-salt stages (seven moisture stages, five salt stages) on hyperspectral data. Spectrum mechanism responsive for soil moisture and salinity were analyzed through spectral curves, correlation, and analysis of variance (Anova, AOV), and spectrum mechanism responsive for soil moisture and salinity model were built. Following that, the spectra were optimized using piecewise direct normalization (PDS)-AOV, non-negative matrix factorization (NMF)-AOV, and orthogonal signal correction (OSC)-AOV. The SOM prediction models were then built by integrating these optimized spectra with Stacking ensemble machine learning algorithms (RF, GBM, ANN). Eventually, the lab-optimized spectra were merged with satellite multispectral images to create new image (named REC) for SOM mapping. The results indicated varying impacts of SMC and SSC on spectra, particularly between 1400 nm to 2000 nm, revealing the influence of moisture-salt interaction; the best optimization algorithm (OSC-AOV) with Stacking mitigated the effect of moisture-salt coexistence on spectra (the R2 and RPD of the best models elevated by 0.005-0.267, 0.020-0.374 respectively, RMSE reduced by 0.137-1.817 g/kg); implementing this algorithm on REC significantly improved the accuracy of SOM mapping (R2 elevated by 0.185-0.259, RMSE reduced by 2.615-3.203 g/kg). This study extensively investigated the effects of moisture and salinity on spectra, spanning from laboratory to satellite, offering a novel approach to understanding and addressing the complexities in SOM mapping in salinized environments.

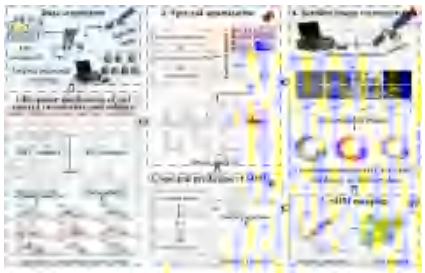


Fig.1. The workflow of this study (SR: Soil reflectance; SOM: soil organic matter; SMC: soil moisture content; SSC: soil salt content; R: original data; PDS: piecewise direct normalization; NMF: non-negative matrix factorization; OSC: orthogonal signal correction).

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# The influence of natural and anthropogenic pyrogenic history of the landscape on soil carbon stocks on example of Komi Republic

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**ABSTRACT**

The soils of Northern regions of Eurasia contain significant carbon stocks. One of the factors influencing the qualitative and quantitative composition of soil carbon is fires. Forest and swamp landscapes are subject of pyrogenic impacts. Low-intensity fires predominate in the study area, which result in complete or partial combustion of forest litter and, in rare cases, the upper organic soil horizons. Partial combustion products of biomass, which are usually represented by aromatic compounds, can enrich the composition of soil organic matter. Moreover, the consequences of the influence of fires on the composition of soil organic matter can be traced back thousands of years, both in the content of benzene polycarboxylic acids (BPCAs) and polycyclic aromatic compounds (PAHs), and in the increase in the content of aromatic fragments in the composition of soil organic matter estimated by $^{13}$ C-NMR. At the same time, swampy forests, which are subject to more frequent fires, despite the smaller thickness of the peat deposit, can contain larger carbon reserves compared to less fire-prone areas with a higher thickness of the peat deposit. In addition, the use of fire during settlement, development of the use of slash-and-burn agriculture, preparation of coal-burning production facilities near the centers of bog ore metallurgy in the 18-20$^{th}$ centuries led to a significant increase in soil carbon stocks of Northern landscapes (5-7 times higher than background values). Thus, given the ubiquity of the pyrogenic factor and the frequency of fires in northern latitudes, fires should be considered as one of the main factors of long-term carbon stabilization in semi-hydromorphic, swamp and anthropogenic soils.

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# Underestimating Soil Carbon Dynamics: The Missing Role of Vertical Transport

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**ABSTRACT**

The radiocarbon content of soil organic carbon (C) is assumed to reflect the carbon's biological reactivity. Large soil radiocarbon ages deep in the soil are interpreted to mean that the C will have a slow response to environmental perturbations such as the effects of warming on the soil microbial C decomposition rate. Here we show that downward advective transport of soil C is an important process affecting soil C ages, leading to an inevitable increase in radiocarbon age with depth even if the decomposition rates remain constant. Thus, the increasing radiocarbon ages of C with depth do not directly imply a corresponding decrease in C reactivity as a function of depth, and instead suggest this C may be as biologically reactive as that nearer the surface. Based on theory and an independent assessment of soil C decomposition rates, the radiocarbon profiles (and content for a given depth) were calculated for over 3000 soils in the USA, and were compared to observational results based on measured soil radiocarbon. The first-order coherence between the two entirely differing approaches suggests the fundamental importance of transport, and the implication that the soil C decomposition rate constant may be relatively invariant with depth. This has significant implications for the soil C response to the changing climate system. These insights may also help serve to reduce biases in Earth System Models which presently do not match the observed depth patterns in soil C or its radiocarbon content.

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# A long-term global Mollisols SOC content prediction framework: integrating prior knowledge, geographical partitioning, and deep learning models with spatio-temporal validation

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**ABSTRACT**

Recently, Soil Organic Carbon (SOC) content has declined across global Mollisols region due to erosion, intensive agriculture, and other factors, weakening the soil's capacity to buffer climate change and necessitating urgent monitoring of SOC dynamics. Large-scale SOC content monitoring using remote sensing technology faces challenges in extracting advanced features from remote sensing data and mitigating the negative impact of high spatial heterogeneity in SOC content on prediction accuracy. To address these challenges, we collected 8,984 samples, 956,423 Landsat TM/OLI images, shuttle radar topography mission-digital elevation model data, and meteorological data. We developed a Geographic Knowledge Dataset (GEKD) incorporating prior knowledge of soil formation and erosion processes. We then input the GEKD into a Probability Hybrid Model (PHM). In the PHM, we applied a fuzzy Gaussian mixture model to cluster the global Mollisols region and calculate corresponding probabilities. We then built a high-accuracy SOC content prediction model by integrating the Attention mechanism, Convolutional Neural Networks, and Convolutional Long Short-Term Memory Networks (A-CNN-ConvLSTM). Finally, we generated spatial maps of SOC content at a 30 m resolution for 8 periods since 1984 and verified the accuracy of its spatial distribution and temporal variation patterns. The results showed that (1) the highest SOC content prediction accuracy (RMSE=7.17 g/kg, R2=0.72, and RPIQ=1.92) was achieved when GEKD was input into PHM using the A-CNN-ConvLSTM algorithm. (2) PHM effectively reduces the negative impact of high SOC spatial heterogeneity on prediction accuracy, resulting in smoother spatial distribution at cluster boundaries. Compared to the global model, PHM reduced RMSE by 1.66 g/kg and improved R2 and RPIQ by 0.06 and 0.15, respectively. (3) Compared to the commonly used random forest algorithm, A-CNN-ConvLSTM reduced RMSE by 1.50 g/kg and improved R2 and RPIQ by 0.13 and 0.47, respectively. The spatial context features extracted by the CNN structure in the A-CNN-ConvLSTM algorithm are the most effective in improving SOC content prediction accuracy. (4) Currently, the SOC content across continents in the global Mollisols region is ranked as follows: Siberia (27.21 g/kg) > Europe (26.78 g/kg) > Asia (20.48 g/kg) > North America (20.43 g/kg) > South America (16.49 g/kg). Since 1984, SOC content has shown a decreasing trend, with the global Mollisols region losing 1.91 g/kg overall. The Asian Mollisols region experienced the largest decline (2.93 g/kg), while Siberia saw the smallest decrease (1.45 g/kg).

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# Field NIR Spectroscopy for Soil Carbon Monitoring in Hazelnut Orchards

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**ABSTRACT**

Monitoring organic carbon stocks in soil is increasingly in demand to support policies on greenhouse gas emissions control, soil quality and carbon farming. This study investigates the application of a rapid and field method based on Near-Infrared (NIR) spectroscopy, in hazelnut orchards in central Italy. Three different plantation ages of hazelnut orchards (<10 years, 20-30 years, > 40 years) were selected within four different farms in Viterbo province.

For each age class, three field replicates were sampled, resulting in 36 soil cores. Depth profiles were not uniform across orchards: while some sites were sampled at standard layers (0–15, 15–30, 30–45 cm), others extended down to 75 cm or were subdivided into uneven intervals according to local soil conditions. In total, these cores produced 108 soil samples. NIR spectra were acquired using the NeoSpectra Scanner both in situ, on moist field samples, and in the laboratory after drying at 40 °C. Because the number of horizons varied among cores, the number of NIR scans per soil augerings was not constant. Overall, the NIR dataset includes approximately 370 spectra, capturing both field and dry conditions and allowing the evaluation of moisture effects across heterogeneous depth profiles.

Given the strong influence of water on NIR measurements, the External Parameter Orthogonalization (EPO) method will be applied to correct moisture-induced spectral distortions and improve SOC prediction accuracy. The aims of the study are: (i) comparing the performance of NIR spectroscopy for SOC stock prediction under field and laboratory conditions; ii) analyzing SOC stock variations with the age of the hazelnut orchards, to determine the role of this crop in the carbon sequestration.

The results will support the development of rapid and cost-effective soil carbon monitoring strategies, providing a structured methodological framework also for carbon credits certification.

**Keywords:** Proximal soil sensing, Soil Spectroscopy, Carbon farming, Carbon sequestration, Hazelnut Orchards

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# Supporting environmental sustainability by increasing soil carbon sink through biowaste recycling and remote sensing integrated with machine learning

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**ABSTRACT**

Expanding soil carbon sinks through biowaste recycling and fertilization management is a land use strategy with potential for achieving net-zero carbon emissions. Nevertheless, the key of this approach relies on the transformation of exogenous carbon into decomposition-resistant forms and a practical and sensitive technique that can identify the change in soil organic carbon (SOC) contents. Thus, in this study, different plots in a Napier grass (*Pennisetum alopecuroides*; a potential bioenergy crop) field in northern Taiwan were treated with a manure compost, a chemical fertilizer, or manure compost plus chemical fertilizer for 40 weeks. Then, the topsoil (0–15 cm) was physiochemically fractionated into a plant-residue forming light fraction, an aggregate-bound heavy fraction, and silt/clay-bound oxidizable and non-oxidizable fractions, with varying SOC contents. The results showed that in the combined treatment group, the tillage-induced soil disturbance and nutrient-driven bacterial activity, indicated by reduced aggregate stability and elevated 16S ribosomal DNA counts, likely facilitated the shift of SOC from an aggregate occluded form (heavy fraction) to organo-mineral complexes (oxidizable fraction), which led to a 5 to 15% enrichment in the stable soil carbon sink. Additionally, grass shoot biomass was 20% higher in the combined treatment group than in the control. On the other hand, this study assessed the robustness of a visible and near-infrared (VIS-NIR) spectrum-based Cubist model trained with Walkley-Black (WB) method measured SOC data (n = 400) from diverse land uses and soil types in Taiwan. Additionally, SOC contents by other wet chemistry approaches—including total organic carbon (TOC) analyzer, elemental analyzer (EA), and loss-on-ignition (LOI) methods—from an independent sample set (n = 46) were introduced to test model's practical applicability across References methods. The model achieved a R2=0.72, RMSE=1.09, RPD=1.88, RPIQ=1.46, and LCCC=0.82. The major model predictors indicated the occurrence of SOC with different stabilities, where degradation was promoted by soil weathering and stabilization was associated with iron oxides. Model-predicted SOC contents also aligned closely with TOC (LCCC = 0.81) and EA (LCCC = 0.76) methods, but less with LOI method (LCCC = 0.48), due to its overestimation from loss of structural water in clay. Overall, this study constructed a practical scheme for soil carbon sink enhancement using biowaste recycling and nondestructive measurement using Vis-NIR-based machine learning model, may be a promising strategy for achieving environmentally sustainable development.

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# Engineered biochar amendments to address multiple soil constraints: Results from 12 field studies

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## ABSTRACT

Soil constraints resulting from sodicity or acidity significantly limit production across Australian cropping systems, with losses in productivity estimated at around A$2B annually. Internationally, these same soil constraints impact food security and sustainability, especially under increasingly variable rainfall. A partnership between the Grains Research and Development Corporation and the New South Wales Department of Primary Industries and Regional Development aims to address these constraints through the development and evaluation of Next Generation Soil Technologies (NGSTs), evaluated in diverse agro-climatic zones across the state of New South Wales, Australia. This presentation will focus on data from 6 field trial sites in 2024, and 12 field sites in 2025; where engineered biochar-mineral composites, multi-functional organic amendments and nano-structured biochar/ lime and gypsum formulations were deployed. These novel amendments have been designed to address potential shortcomings with traditional amendments, including the slow dissolution rate of agricultural lime and the challenges faced in addressing constraints that occur in the sub-soil.

Results from the 2024 field trials indicate that NGST efficacy varies considerably across soil types and agro-climatic zones. Biochar-mineral composites and multi-functional organic amendments demonstrated greatest efficacy at some sites with sodic, dispersive soils, achieving yield responses which exceeded conventional gypsum amelioration. Site-specific factors including soil type, constraint severity, and seasonal rainfall appear critical determinants of treatment response. Ongoing multi-year evaluation will assess persistence of amelioration effects and improvements to sub-soil extraction of water and nutrients. Statistical analysis of 2024 yield and biomass data was conducted using linear mixed models and showed that significant treatment effects were detected at several sites. For example, in a sodic dispersive subsoil, the control was no different to gypsum (2t/ha) incorporation (traditional amendment) resulting in 4.30 t grain/ha ($p<0.01$), while the deep placement of a stoichiometrically balanced organic amendment or an engineered biochar containing soluble Ca resulted in yield exceeding 5.1 t grain/ha ($p<0.01$). Results from these field evaluations will begin to elucidate mechanisms of action of engineered biochar products.

The presentation will cover some of the logistical challenges of amending soils to address sub-soil constraints, and how this was overcome through optimizing pellet formulations and dimensions. For these products to be practically applied, it needs to flow freely through agricultural equipment and be structurally stable for transport and handling. Insights will be provided for commercialization of NGSTs to facilitate enhanced agricultural productivity.

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# Can we grow food on the Moon? Engineering biological systems in lunar regolith

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## ABSTRACT

Future lunar exploration requires self-sufficient food production. However, lunar regolith provides a hostile environment that lacks the biological and physical properties necessary for cultivation. Developing functional soil from regolith requires engineering three core components: biological, chemical, and physical properties.

Here, we evaluated the foundational requirements to grow lettuce on The Lunar Highlands Simulant (LHS-1), a high-fidelity mineral analogue that closely resembles Apollo-collected samples (Easter *et al.* 2022). Continuous $^{13}C$-$CO_2$ labelling at 500 ppm with $^{13}C$ endmember at 15atom% was used to trace carbon (C) cycling pathways. A fully factorial design was evaluated against an unamended control: 1) Earth microbiome transplant, 2) biosolids biochar (HTT 500ºC, 5% w/w), and 3) synthetic root exudates (0.22% C w/w soil). Transplanting microbial communities – achieved by placing donor soil on filter paper above tubes of receiver soil and washing through with water for two weeks – has proven effective for establishing beneficial microbiomes and restoring essential soil functions in novel environments (Howard *et al.* 2017). Biochar, a C-rich pyrolysis product, provides an organic matrix that supports microbial function while simultaneously improving water retention, reducing bulk density, and mitigating metal toxicity. In addition, it will be technically feasible to pyrolyze biosolids generated during lunar exploration into biochar, recycling nutrients in a closed-loop system while eliminating biosecurity risks. With plants delivering up to 40% of their photosynthetically fixed C to microbes at the root surface in established systems, a cocktail of various C substrates was incorporated as immediate food for the microbial community. After 68 days, lettuce growth, soil chemistry and microbial community composition were assessed as indicators of regolith transformation. Source partitioning using $^{13}C$ isotopic signatures was used to trace C cycling pathways and determine the fate of C allocation in amended lunar regolith.

Preliminary results demonstrated that the addition of biosolids biochar increased lettuce production more than 5-fold compared to treatments without char. Microbiome transplantation was the dominant driver of community structure, explaining about 13% of variance in bulk-soil bacteria and 22% in root bacteria, compared with 3–10% for biochar and synthetic root exudate addition. Microbiome transplantation explained 7–9% of variance in fungal community composition, with modest additional effects from interactive explanatory variables. Through recycled biosolids and engineered microbiomes, this study transforms regolith into a living soil that is capable of supporting plant growth, establishing the biological foundation for sustained human habitation on the lunar surface.

**Keywords:** Lunar regolith transformation, microbiome transplantation, biosolids biochar, carbon cycling, $^{13}C$ isotopic labelling

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# Short term impact of biochar on soil total carbon, total nitrogen, $\delta^{13}C$ and $\delta^{15}N$ in two vineyards in Southeast Queensland of subtropical Australia

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## ABSTRACT

Biochar is a potential regenerative viticulture (RV) tool to increase vineyard soil carbon (C) and restore vineyard soil health, improve ecosystem services and mitigate against extreme climatic events, yet its impact on subtropical vineyard soils remains limited. This study used a dual stable isotope analysis approach to evaluate the short-term impacts of pine biochar on soil total C and total nitrogen (N) and their isotope compositions ($\delta^{13}C$ and $\delta^{15}N$) in the top 0 – 30 cm of two Southeast Queensland vineyards in subtropical Australia.

Pine biochar (650°C pyrolysis) was applied at 0, 5.0, 10.0 and 20.0 t $ha^{-1}$ to the vine rows (VR) soil at two vineyards, Nuova Scuola (NS, clay-loam soil) and Ballandean Estate (BE, sandy soil) in August 2023. Soil samples were collected at sample depths of 0 – 10 cm, 10 – 20 cm, and 20 – 30 cm of the VR and mid row (MR) soils in Spring 2023 and Summer 2024, one day before Harvest. Soil total C, total N and their stable isotope compositions ($\delta^{13}C$ and $\delta^{15}N$) were measured. Biochar had muted effects on the clay–loam soil of NS with little mobility through the soil depths. In contrast, the sandy soil of BE was more responsive, with increased total C, total N and enriched $\delta^{15}N$, and biochar movement down the soil profile. Differences in VR and MR were associated with vegetation inputs, soil microbial activity and chemical use (fungicides and herbicides).

The $\delta^{13}C$ enrichment in the sandy soils indicated clear incorporation of biochar-derived C into the soil matrix, consistent with improved soil water retention and microbial accessibility. In contrast, $\delta^{13}C$ shifts at the clay-loam soils were smaller, reflecting dominant organo-mineral associations and stronger buffering capacity. Patterns in $\delta^{15}N$ revealed divergent N cycling pathways: MR soils showed $^{15}N$ enrichment indicative of intensified microbial N processing and potential N loss, while VR soils at the clay-loam site maintained a more closed N cycle.

The dual stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) approach provided a sensitive diagnostic framework for fingerprinting soil C and N transformations in biochar-amended vineyard soils. These findings demonstrate that pine biochar can meaningfully alter soil biochemical processes within 6 months, with outcomes strongly influenced by soil texture. This work supports site-specific biochar management strategies aimed at enhancing vineyard soil health and advancing climate-smart regenerative viticulture.

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# A simple gravimetric proxy for rapid, low-cost estimates across diverse subtropical soils

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**ABSTRACT**

Soil Organic carbon (SOC) is fundamental to sustaining soil health and moderating climate, yet conventional laboratory analyses and advanced sensing can be prohibitive and logistically demanding at fine spatial scales. We evaluated a low-tech, gravimetry-based proxy that leverages the coupling between organic matter and water retention to estimate SOC using only an oven and a balance. We assessed 11 subtropical Australian soils across a range of contrasting textures, subject to varied disturbance regimes. As a single predictor, the proxy provided a modest relationship with laboratory SOC methods ($R^2 \approx 0.2$-$0.4$; $p=0.001$). However, introducing minimal profile context substantially improved performance to $R^2 \approx 0.7$-$0.9$ ($p<0.001$) while preserving very low cost and operational simplicity. The procedure is inexpensive, fast, and easily adopted by practitioners without spectroscopic or remote-sensing infrastructure, though has potential to complement existing methods. While broader validation beyond the initial 11 soils is required, the approach shows promise for scalable SOC identification and monitoring. It may be used for identifying hotspots/coldspots, guiding sampling intensity, and complementing higher-end methods, without dependence on instrument-specific libraries. Overall, this work demonstrates that simple gravimetric measurements can deliver actionable SOC insights at scale and at low cost.

**Keywords:** SOC; moisture; proxy; low-tech; carbon

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# Biochar–microbial interactions as drivers of soil carbon sequestration: from heterotrophic priming to autotrophic $CO_2$ fixation

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## ABSTRACT

Pyrogenic carbon (PyC), represented by biochar in agricultural application, is increasingly recognized as a critical lever for climate mitigation and soil sustainability. However, pyrogenic carbon has historically been framed as a passive, physiochemically stable carbon pool, whereas the microbial mechanisms that actively govern its role in soil carbon stabilization and transformation remain largely unresolved. Here, we synthesize mechanistic insights, incubation experiments, and field-scale functional analyses to demonstrate that biochar operates as a dynamic microbial interface that restructures soil carbon cycling through both heterotrophic and autotrophic pathways. Biochar–microbe interactions are governed by coupled physical, chemical, and electrochemical mechanisms [1]. Biochar modifies microbial habitats via pore-mediated colonization, nutrient retention, and pH buffering, while simultaneously participating in extracellular and interspecific electron transfer, altering redox-sensitive metabolic pathways. These mechanisms regulate microbial activity, community assembly, and signaling processes, positioning biochar as an active mediator of soil biogeochemical reactions rather than an inert carbon reservoir. Biochar-induced priming effects on native soil organic carbon (SOC) are driven by shifts in microbial community structure and metabolic functions rather than by carbon recalcitrance alone [2]. High-temperature biochar enhances SOC stability by maintaining physicochemical homeostasis and selectively favoring microbial consortia associated with reduced heterotrophic disturbance, enhanced electron transfer capacity, and secondary metabolite turnover. These results identify microbial accessibility and functional redundancy as key controls on carbon persistence in biochar-amended soil. Additionally, biochar activates an often-overlooked autotrophic carbon sequestration pathway. Biochar significantly restructures Calvin cycle–driven $CO_2$ fixation by regulating the abundance, activity, and community composition of *cbbL*- and *cbbM*-harboring autotrophic microbes [3]. The rhizosphere emerges as a hotspot of autotrophic $CO_2$ assimilation, with biochar effects mediated by soil pH, redox potential, nitrogen availability, and labile carbon pools. Importantly, autotrophic $CO_2$ fixation is functionally coupled with nitrogen, iron, methane, and arsenic cycling, linking PyC systems to broader biogeochemical cycles. By integrating heterotrophic carbon protection with autotrophic carbon input, future research is expected to move beyond passive representations of pyrogenic carbon and incorporate microbially mediated regulation to better constrain long-term soil carbon sequestration.

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# Biochar at scale needs long-term proof: LTE field trials supporting the green transition of Danish agriculture

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**ABSTRACT**

Pyrogenic carbon (biochar) is increasingly positioned as a climate-smart soil amendment, yet robust long-term evidence under cool-temperate, high-yield farming systems remains scarce. Denmark is now moving toward large-scale biochar deployment as part of national climate policy, creating an urgent need for practice-near data on agronomic performance, carbon persistence, and potential risks to soil–water systems. Here we present the Danish Biochar LTE (Long-Term Experiment), a coordinated platform designed to generate the empirical foundation required for regulation, greenhouse-gas accounting, and sustainable implementation. The platform is supported by a 10 Mio. € grant from the Ministry of Green Transition.

A key novelty is the Danish focus on producing biochar from biogas residue fibers (BRF), a widely available, circular-economy feedstock from anaerobic digestion, pelletized and pyrolyzed under controlled, industrial conditions (600°C, >1 h residence time). This next-generation pyrogenic-C pathway links waste-stream valorisation to soil carbon sequestration and creates a distinct biochar type with properties and co-benefits that remain poorly documented in field settings. The LTE in addition includes biochars from straw, wood, and sewage sludge, produced at established full-scale plants, enabling traceable, reproducible product batches.

Field trials are established at four research-managed sites spanning Danish soil and climate gradients. Treatments compare annual low-dose inputs (1 t biochar-C/ha/yr) versus a single high-dose application (10 t biochar-C/ha). Biochar is incorporated into the upper 20-25 cm and a comprehensive monitoring program targets crop yield and nutrient use, soil physical functioning, carbon stabilization, microbial and biogeochemical responses, and environmental safeguards, including nitrate and contaminant leaching measured via suction cups at 1 m depth and complementary worst-case leaching tests performed with lysimeters.

By integrating industrially produced BRF-biochar with replicated, multi-site long-term field experimentation, Danish Biochar LTE provides a timely testbed to connect to inform on climate mitigation outcomes and risk-informed governance of pyrogenic-C in agriculture.

**Acknowledgments**

The Danish Biochar LTE is a collaborative project led by scientists from Aarhus University and the University of Copenhagen, and we thank all participants for their contributions. The skilled support of technical staff in the field has been instrumental to the successful establishment and operation of the experiments, as has the assistance of laboratory staff in sample processing and analysis.

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# Resolving Organic-Inorganic Carbon Overlap: Comparing Soil Organic Carbon (SOC) Measurement Methods to Improve Accuracy in Calcareous Soils

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## ABSTRACT

Accurate quantification of soil organic carbon (SOC) is essential for evaluating soil quality, modeling carbon cycling, and supporting soil carbon accounting frameworks. However, SOC estimates can vary substantially among analytical methods, particularly in soils containing measurable soil inorganic carbon (SIC), where incomplete carbonate removal or thermal overlap can bias results. This study evaluated the accuracy and applicability of commonly used SOC measurement methods across soil layers differing in SIC content under two land uses: cultivated land and adjacent deciduous forest.

Forty-five soil profiles were sampled to 100 cm depth, each with five depth increments (0–5, 5–15, 15–30, 30–60, and 60–100 cm). SOC was quantified using (i) dry combustion following acid fumigation and (ii) an indirect method based on total carbon (TC) minus SIC after muffle furnace treatment. Loss-on-ignition (LOI) was also evaluated as an estimate of soil organic matter. Soil inorganic carbon was also independently measured using a digital manometer–based Calcimetry method to determine SIC thresholds affecting method accuracy.

SOC values obtained by acid fumigation and the indirect method were comparable in soil layers where SIC was low (~ 3%), particularly within the upper 60 cm of the soil profile. However, method divergence increased markedly in carbonate-rich subsoils (60–100 cm), where SIC exceeded ~5%. In these horizons, acid fumigation did not completely remove inorganic carbon, resulting in systematically inflated SOC estimates, whereas SOC derived from TC–SIC subtraction remained consistent with expected subsoil carbon levels. LOI showed strong correlations with SOC in surface horizons but exhibited depth-specific conversion factors, indicating that a single SOM-to-SOC conversion factor is unsuitable across the soil profile.

These findings demonstrate that SOC method accuracy is strongly controlled by measured SIC content. Acid fumigation is appropriate only when SIC is low, whereas the indirect method provides more reliable SOC estimates in carbonate-rich subsoils. The integration of digital calcimetry allows identification of practical SIC thresholds and highlights the critical need to quantify SIC when selecting or interpreting SOC analytical methods in soils containing carbonate-bearing horizons.

# Life Cycle Assessment of Traditional Japanese Thatched Roofs with Biochar End-of-Life Integration: Implications for Carbon Mitigation

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**ABSTRACT**

Traditional Japanese thatched roofs constructed from locally sourced grasses such as *Miscanthus sinensis* and *Phragmites australis*, represent a renewable building material with cultural heritage value. Beyond their historical significance, these biomass-based materials offer untapped potential for climate mitigation. This study evaluates their potential as a climate mitigation strategy through a cradle-to-grave life cycle assessment that incorporates biochar production at end-of-life. The objective is to determine whether coupling traditional roofing systems with carbon-sequestering processes can transform them into carbon-negative solutions. The assessment was conducted using Brightway2 in Python, modeling cultivation, transport, installation, and end-of-life conversion to biochar under a functional unit of one square meter of roof area over a 30-year service life. Inventory data included fertilizer and diesel inputs, transport distances, and pyrolysis energy requirements. Environmental flows accounted for biogenic carbon dioxide uptake during plant growth, nitrous oxide emissions, nitrate leaching, and permanent carbon storage in biochar with stability exceeding one thousand years. Contribution analysis was used to identify the most influential life cycle stages, and sensitivity tests examined the impact of parameters such as electricity carbon intensity and biomass yield. Comparative benchmarking against conventional roofing materials, including ceramic tiles, metal sheets, and asphalt shingles, was also performed to contextualize potential climate benefits. The findings indicate that integrating biochar production into traditional thatch systems can significantly enhance their environmental performance by leveraging long-term carbon sequestration. Preliminary modeling suggests that end-of-life strategies and cultivation practices are critical drivers of overall climate impact, while sensitivity analysis highlights energy-related processes as the most influential factor, underscoring the importance of low-carbon electricity in pyrolysis operations. This research demonstrates a pathway for linking heritage architecture with modern carbon management strategies, offering a scalable approach to low-carbon construction.

**Acknowledgments**

We thank the Japanese Thatcher Association for generously sharing their aged thatch, the students who worked tirelessly to prepare it as biochar, and the University of Tsukuba for funding and supporting this research. The old thatch used in this study was obtained during reroofing work with the cooperation of Earth Building Co., Ltd. (Representative Director: Mr. Okimoto Taichi).

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# Methodological insights in the determination of soil SOC:clay ratio at farm level in Southern Belgium

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## ABSTRACT

Soil organic matter is a key soil property of soil functioning and its capacity to deliver major ecosystem services. But it has undergone a substantial decline in cultivated soils worldwide, urging the needs for preservation and restoration practices for sustainable agricultural land management.

The SOC-to-clay ratio has been proposed by some authors as a metric of soil quality as it correlates with aggregate structural stability. Despite scientific debates about the relevance of this indicator, it has been the central point of an agri-environmental scheme in Wallonia (MAEC Sol).

This study evaluates the methodological basis for implementing the SOC/clay indicator within the MAEC Sol Assessing soil organic carbon (SOC) at farm scale requires robust indicators and sampling strategies capable of capturing spatial and pedological heterogeneity.

Using detailed soil maps and geostatistical simulations of SOC spatial variability, we assessed the performance of multiple sampling designs across homogeneous soil zones. Results show that pedological units derived from high-resolution soil maps are highly relevant for predicting clay content, whereas SOC variability is primarily driven by management. Comparison with measured granulometry revealed substantial uncertainties in clay estimates from existing soil texture maps (mean absolute error ≈ 4.6%), emphasizing the need for improved cartographic products. Geostatistical modelling demonstrated that ≥20 subsamples collected in a zig-zag pattern provide robust estimates of zone-level SOC means.

The assessment scheme at farm level is based on (i) the characterization of a selection of homogeneous zones defined by soil type, land use and levels of organic restitutions, and (ii) the extrapolation of measurements to the similar unsampled plots. A specific web-application was developed within the REQUASUD structure allowing farmers to delineate limits of parcels and laboratory operators to identify the selection of sampling zones. In a feasibility study, we compared the diagnosis made at farm level based on measurement of soc:clay ratio on every plot to the diagnosis made upon the selection of plots. Results for a selection of 15 farms show that the both approaches do not differ significantly.

Together, our findings confirm the scientific validity of the approach implemented to use the SOC/clay ratio as a soil quality metric at farm level and highlight the essential role of detailed soil mapping and geostatistical approaches for its reliable implementation at operational scales.

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# Intercropping Enhance Agricultural Production and Increase The Level of Carbon in The Soil

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**ABSTRACT**

Global food security is increasingly threatened by the adverse consequences of interrelated environmental problems, including climate change, biodiversity loss, and pollution, also referred to as the triple planetary crisis. In response to these challenges, comprehensive strategies for designing sustainable agri-food systems, such as agroecology, have recently gained significant interest. It is therefore important to optimize good agricultural practices by turning to methods such as intercropping.

These can increase crop yields, effectively control pests, and optimize carbon sequestration in the soil, thereby contributing to the dynamics of soil carbon stocks, which have a significant impact on atmospheric chemistry and the global carbon cycle.

Carbon sequestration in the soil is an essential process in combating climate change, as it allows carbon present in the atmosphere to be stored in the form of stable organic matter. This storage also contributes to improving soil structure, fertility, and water retention capacity. In addition, carbon-rich soil promotes biological activity and improves the resilience of agricultural systems. Therefore, carbon capture is both an environmental strategy and a driver of sustainability in agriculture. This study aimed to assess the impact of intercropping on soil carbon sequestration.

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# Uncertainty of Vis–NIR–based models for predicting soil organic carbon using Monte Carlo simulation

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**ABSTRACT**

Soil is regarded as the largest and most promising carbon sink. Therefore, the rapid and efficient measurement of soil organic carbon (SOC) is crucial for estimating soil carbon sequestration capacity. Conventional destructive wet chemical methods for determining SOC are time-consuming, labor-intensive, and generate chemical waste. Visible and near infrared (Vis–NIR) spectroscopy can detect the molecular vibration spectra of organic matter, and when combined with machine learning algorithms (e.g., Cubist), it enables rapid and non-destructive SOC prediction. However, uncertainty still exists in the models of SOC measurement. This dry chemistry approach represents a promising tool for carbon sink assessment. The study aimed to integrate soil Vis–NIR spectral data with the Cubist algorithm and Monte Carlo uncertainty analysis to develop an SOC prediction model calibrated with the total organic carbon (TOC) analyzer method. Additionally, the predictive performance of in-situ Vis–NIR spectral data using the TOC-based SOC model was evaluated. A total of 1,600 soil samples were collected in Taiwan, including both Vis–NIR spectra and SOC data measured by the TOC method. After confirming the absence of outliers in the spectral dataset using Mahalanobis distance, 200 samples were randomly selected as the validation set, while the remaining 1,400 samples were further divided into calibration sets of 200, 400, 600, 800, 1,000, 1,200, and 1,400 samples to compare model performance across different sample sizes. The results indicated that the model calibrated with 1,000 samples achieved the best predictive performance ($R^2$ = 0.64, RMSE = 0.18, RPD = 1.67, and LCCC = 0.80). Furthermore, to assess the applicability of the in-situ Vis–NIR SOC model, 19 field sites were selected as demonstration areas. The evaluation results showed an overall RMSE of 0.83% between the model-predicted and TOC-measured SOC values, with the best fit observed when SOC contents were below 3%. Based on the analysis of model variable importance, the key spectral bands influencing SOC prediction were identified. These wavelengths can serve as References for developing portable narrow-band Vis–NIR spectrometers, thereby enhancing the potential of in-situ Vis–NIR non-destructive SOC monitoring and measurement for field-scale carbon sink assessment.

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# Innovation and Application of Targeted Humification of Agricultural Wastes and Targeted Soil Improvement Technologies

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**ABSTRACT**

Agricultural development in China faces the dual constraints of increasing organic waste accumulation and declining soil fertility. Large quantities of crop residues and livestock manure remain inefficiently utilized due to low humification efficiency and slow lignocellulose degradation, particularly under low-temperature and oxygen-limited conditions. This study developed and evaluated a targeted humification and soil amelioration framework to enhance organic waste transformation and soil functional restoration.

We established a theory of directed humification based on targeted microbial consortium assembly and microenvironmental regulation. A composite microbial system consisting of psychrophilic bacteria, phosphate-solubilizing bacteria, *Pseudomonas*, *Bacillus*, *Streptomyces*, and *Clostridium* was constructed to enable low-temperature initiation, sequential lignocellulose degradation, and carbon stabilization. The initiation temperature for decomposition was reduced to 0-5 °C, and over 90% straw degradation was achieved within 7 days. Compared with conventional composting, humification efficiency increased by 20%-24%, fulvic acid content increased by 6%, soluble organic carbon by 11%, and total organic carbon retention by 22%, while humic acid content was maintained.

A microenvironment-regulated humification technology was developed to couple lignocellulose decomposition with the directed synthesis of soil functional amendments. The decomposition period was shortened to 7-15 days, and active humic fractions increased by 12.8%. Using humified organic matter as a carrier, a suite of soil functional materials was formulated, including organic-mineral composite aggregate stabilizers, carbon-based pH conditioners, nutrient activators, growth-promoting biofertilizers, and disease-suppressive microbial conditioners. The microbe-material interface regulation strategy integrating biological driving, interface construction, nutrient regulation, and environmental control was proposed to enhance soil structural, chemical, and biological functions.

A targeted soil improvement and land-use integration model was established, combining crop rotation, residue return, biological constraint mitigation, pH regulation, and water-nutrient conservation with precision fertilization and intelligent fertigation. Field implementation from 2022 to 2024 treated 1.8 million tons of agricultural waste and improved 6 million mu of farmland. Soil fertility increased by 0.5-1 grade, soil organic carbon increased by 3-8%, carbon emissions were reduced by 0.8-19 t $CO_2$ eq $ha^{-1}$, and soil carbon sequestration increased by 0.14-4.2 t $CO_2$ eq $ha^{-1}$. Crop yields increased by more than 8%, demonstrating that directed humification provides an effective pathway for agricultural waste valorization, soil functional restoration, and climate-smart agriculture.

**Key Words: Targeted humification, Agricultural Wastes, Soil functional amendment, Carbon sequestration**

# Challenges and Coping Strategies for the Journals of Soil Science in China

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**ABSTRACT**

The high-quality development of academic journals is of common concern to journal editors, editorial board members, paper authors, and readers. High quality journals require the support of excellent manuscripts, and high-quality academic papers drive the high-quality development of journals. In the past 20 years, the number of papers written by Chinese scholars and published in various academic journals has significantly increased, but most journals published in China are facing the challenge of insufficient high-quality manuscript sources. This article provides a brief analysis of the specific problems and possible solutions in soil science journals published domestically in China.

There are three main challenges:

1. The number of journals and the number of publications per journal are limited

At present, the number of Chinese and English journals that mainly publish research papers in the field of soil science in China is very limited, and the number of publications in each journal is also not high. Due to the limited publication capacity of journals, the publication period of papers is relatively long. It usually takes 1-2 years from paper submission to formal publication.

2. The quantity of scientific achievements has significantly increased, and the publishing capacity of journals is unable to meet the demand

Chinese government attaches great importance to agriculture and environmental issues, and the government's investment in research activities related to soil science has been increasing year by year; On the other hand, the number of researchers engaged in soil science investigation is also constantly increasing. Therefore, in the past 20 years, the number of scientific achievements related to soil science has been continuously increasing. However, due to the limited ability of domestic soil science journals to publish papers, most of the relevant research results have been published in English in international journals.

3. The quantity of high-quality articles is insufficient, and the quality of soil science journals needs to be improved

Similar to other disciplines, due to the fact that most of the research papers in the field of soil science written by Chinese authors are submitted and published in international journals, the number of high-quality articles in domestic journals in China is insufficient, and the quality of journals needs to be improved.

Coping strategies are as follow”

1. Increase the number of journals in the field of soil science

Chinese government is encouraging the establishment of new academic journals to publish more scientific research results. In recent years, some new academic journals, including soil science journals, have been launched.

2. Increase the number of articles published in soil science journals and shorten the publication period

Chinese government is encouraging existing academic journals to increase the number of published papers in response to the increasing demands for publishing scientific achievements.

3. Enhance the influence of soil science journals both internationally and domestically, and attract high-quality manuscript sources

By improving the quality of soil science journals and strengthening publicity and promotion activities, the journal's influence will be enhanced both internationally and domestically, and more excellent articles will submit to the journals. The publication of high-quality papers will further enhance the quality and influence of soil science journals.

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# The Role of Scientific Societies and Their Journals to Foster Trust in Science

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**ABSTRACT**

Public trust and support for science are essential to successfully address the global challenges of climate change, ecological sustainability, human health, and resource use. To serve the public good at the highest level, scientists adhere to values and practices that must be understood, maintained, and improved as societal needs and technology change. What can scientific societies such as SSSA and IUSS do to help maintain and modernize the highest standards for science in the coming years, especially as artificial intelligence (AI) revolutionizes key steps in the scientific process? Here we propose to expand the service and educational platforms for students, early career scientists, and scientists in general.

In this presentation, we discuss how scientific societies can provide educational resources like online short courses, webinars, in-person workshops, and mentoring opportunities for students. These programs would focus on general topics like preparation of manuscripts, experimental design, considerations of scale in sample collection and data interpretation, data management, interpretations and assumptions of all statistical procedures, how to embrace uncertainty in scientific research, ethical use and reporting of data, use of AI – its dangers and appropriate uses, patterns of logical inference – with or without statistics, and other relevant topics. Such guidelines need to be continuously adapted as AI tools further develop. In addition, scientific societies play an important role in providing a platform for publication of scientific results, reviews and discussions, and comprehensive surveys of methodology. Journals, books, and newsletters published by scientific societies are important for the dissemination of scientific ideas, results, and impacts. In contrast to commercial publishers, scientific societies keep their ownership and responsibilities over the editorial process and quality control, and so can foster trust in science.

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# Evolution of Global Soil Science Collaboration Networks and Its Implications for Journal Development

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**ABSTRACT**

Soil science plays a critical role in addressing global challenges such as climate change, food security. Advancing this field therefore requires research that integrates cross-regional data and leverages multinational expertise. For academic journals, understanding how global scientific collaboration evolves is not only about improving citation metrics, but also about fostering a more integrated and inclusive research ecosystem. Based on soil science publications from the Web of Science Core Collection (1995–2025), this study employed Social Network Analysis and bibliometric indicators to examine co-authorship networks at national and institutional levels, aiming to quantify the interplay between collaborative structures and research quality. Results show that the global soil science network has evolved from a more fragmented state toward a denser, more connected system with a pronounced small-world tendency, implying more efficient reachability for knowledge exchange. The network has shifted from early single core dominance toward a polycentric, multi hub configuration in which emerging hubs, most notably institutions in China, have increasingly strengthened their bridging role alongside established centers. International collaboration is positively associated with publication quality. Internationally coauthored papers are more likely to be published in Q1 journals, with an odds ratio of 1.44 to 1.94 for international versus domestic papers across the six time slices. Furthermore, a clear collaboration gradient is observed. When collaboration involves five or more countries, the share of papers entering the within year top 10% most cited group reaches 26.6%, compared with 9.2% for single country papers. This suggests that broad global connectivity significantly enhances the scientific robustness of soil research. Thus, journals should play an active role in connecting the global scientific community. First, aligning with the trend towards polycentricity, journals should foster inclusive editorial networks involving scientists from diverse regions. Second, recognizing that high-quality research relies on cross-regional validation, editorial strategies should prioritize curating themes focused on transnational comparative studies and global-scale synthesis, thereby facilitating the integration of fragmented local knowledge into generalized theories. Finally, in the era of Open Science, journals must champion data standardization and the FAIR principles. By removing technical barriers to collaboration through transparent data policies, journals can help build a cumulative, reproducible, and highly collaborative knowledge base for the future of soil science.

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# Soil as Component of Ancient Adobe, Mudbricks, Mortar, and Plaster: Investigation of Engineering Structures of The Past in Oman

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**ABSTRACT**

Soil is a vital material of old structures (buildings, aqueducts, liners of irrigation channels, etc.) that form the architecture and cultural heritage of Oman, enduring for millennia. his research investigates soil cultural ecosystem services, sustainable construction materials, and ancient engineering techniques in Al-Dakhiliyah Governorate, focusing on monuments and ruins in Izki, Nizwa, and Bahla. This research explores how ancient Omanis used local soil to build durable structures. We assess the physicochemical, mechanical, mineralogical and elemental characteristics of the soil used in the old structures and evaluate the cultural and economic values of soil-based heritage sites among local communities and visitors. A mixed method approach was employed by integrating field observations, interviews, laboratory analysis and perception-based questionnaire. Soil samples were collected from different old engineering structures and examined through physical, chemical, mechanical and elemental lab analysis. Simultaneously, a structured survey was conducted to evaluate public perception of the cultural and economic importance of soil-based heritage. The results show that soil used in ancient structures predominantly fall within loam, silt loam and sandy loam textures. Izki soil materials revealed higher clay (25.6%), whereas Bahla ones contained finer silt rich soils (59.7%). The inclusion of plant fibres, straws and shell fragments was found to enhance the durability and improve hydrothermal performance of adobe, mudbricks and other engineered parts of the structures. Elemental analysis confirmed calcite, quartz and dolomite as dominant minerals, which reflect the adaptive use of locally available geological resources and the deep knowledge of traditional builders. Mechanical tests indicated compressive stress ranging between 0.35-20 MPa and bulk densities from 1.38-1.78 g/cm3. The public perception survey highlighted that over 70% of respondents strongly agreed that these sites contribute to Omani cultural identity. Heritage tourism also arisen as an important economic driver: 63.5% of visitors reported spending between 10-50 OMR (26-130 US$) per visit, while 97.1% agreed that improving facilities like guided tours, explaining the value of soil as vital construction materials, and recreational areas, which educate about soil resources, would increase visitation. However, 80% of respondents indicated limited awareness of the role of soil and traditional materials in construction, suggesting the need for enhanced education and interpretive programs. This work demonstrates that ancient Omani builders owned sophisticated knowledge of soil properties in old engineering projects, enabling the creation of structures that remain environmentally and culturally meaningful.

**Keywords:** Key words: Cultural soil, Sustainable construction, Traditional engineering, Earthen architecture, Ancestors.

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# Engaging Youth with Soil Science through an Original Picture Book

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**ABSTRACT**

Soil, as the foundation of terrestrial ecosystems, is indispensable for sustainable development. However, effective communication of soil science remains a challenge, particularly among younger audiences. While general soil science resources exist, there is a noticeable lack of high-quality, original picture books that are both scientifically accurate and culturally relevant for school students.

To address this gap, we developed an original picture book specifically designed for primary and secondary students. This interdisciplinary project integrates expertise from soil scientists, educators, and artists to ensure the content is engaging and pedagogically sound. The book systematically introduces key concepts such as soil formation, material composition, and the science behind soil colors. It builds relatable connections by linking soil types to common foods and introduces cultural context through China's iconic "Five-Colored Soil" tradition. The narrative also addresses pressing environmental issues like soil degradation in China and suggests practical, everyday actions that students can take to protect soil resources.

This presentation will elaborate on the creative strategy and co-development process used to transform ABSTRACT ideas—such as soil profiles, composition, and biogeochemical processes—into visually compelling, story-driven illustrations. We will demonstrate how the book's design fosters curiosity and encourages a sense of responsibility among young readers.

This project shows that a well-designed picture book, grounded in local context and scientific rigor, can serve as an effective bridge between soil science and the public. It offers a meaningful model for enhancing soil literacy and cultivating ecological awareness from an early age, contributing to long-term sustainability education.

**Keywords:** Soil Science Communication; Science Picture Book; Interdisciplinary Collaboration; Public Understanding of Science; Environmental Education

# Analysis and Exploration on the Paths of Experiential Soil Science Popularization towards Primary School Students

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**ABSTRACT**

Soil lies at the center of the terrestrial and ecological environment of the Earth. It is the foundation for agricultural and forestry production and plays a crucial role as an environmental buffer. However, the overall level of public scientific literacy in soil science remains low, and there are marked regional imbalances in soil science popularization efforts. Primary school students are one of the key target groups for science popularization in China in the new era, and experiential science communication can not only help them acquire scientific knowledge, but also deepen their emotional resonance with soil and agricultural sciences. In this study, we first investigate the soil- and agriculture-related knowledge points included in primary school science education. On this basis, we classify the knowledge system of soil science, design and develop experiential soil science popularization courses for primary school students, and carry out science popularization practice activities in university laboratories and soil museums. Finally, we disseminate the courses and typical case videos through online media. The project outcomes have enhanced primary and secondary school students' and the general public's understanding of soil, stimulated their curiosity about and interest in agricultural science, and contributed to leveraging science popularization to support all-round human development and the building of an innovative nation.

**Key words:** Soil science popularization; Primary school students; Experiential learning; Science education;

**Acknowledgments**

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# Multidimensional Sustainability Assessment of Heavy Metal-Contaminated Farmland Remediation: An Environment-Policy-Economy Synergistic Framework and Long-Term Roadmap (2005–2040)

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**ABSTRACT**

Heavy metal contamination in arable soil has escalated into a planetary crisis, severely compromising global food security and posing chronic carcinogenic risks to human health through dietary accumulation. Given the scale of this hazard, the governance of contaminated land is shifting from emergency pollution control to a Green and Sustainable Remediation (GSR) paradigm, which prioritizes minimizing secondary environmental footprints and resource consumption. Against this backdrop, China is undergoing a critical transition from government-centric intervention to market-driven management; however, existing evaluations predominantly focus on short-term technical efficacy, lacking a systemic understanding of the long-term trade-offs between environmental burdens, economic viability, and policy incentives. To address this gap, this study constructs an Environment-Policy-Economy (EPE) ternary synergistic analysis framework. Methodologically, we first diagnose the spatiotemporal evolution of pollution trends from 2005 to 2025, quantitatively isolating the net contribution of landmark policy interventions, such as *the Soil Pollution Prevention and Control Law.* Subsequently, an integrated Life Cycle Sustainability Assessment (LCSA) and Cost-Benefit Analysis (CBA) system is established over a prospective 20-year cycle (2021–2040) to rigorously benchmark diverse remediation technologies, ranging from physicochemical engineering to nature-based solutions. Results indicate a distinct trade-off: while physicochemical measures offer rapid risk reduction, they incur disproportionately high Life Cycle Costs (LCC) and carbon emissions. Conversely, agronomic and biological strategies, though slower, yield superior long-term ecosystem service values and alignment with GSR principles. Furthermore, the economic analysis highlights that the diminishing marginal utility of fiscal subsidies renders the current model financially unsustainable, suggesting that a structural shift toward market-based instruments is essential. By revealing these multidimensional interaction mechanisms, this study provides empirical evidence for optimizing the technological roadmap, ultimately informing the strategic development of China's soil governance towards the 2035 and 2040 sustainability horizons.

# Optimal Organic Amendment Strategies for Safe Utilization of Heavy Metal-Contaminated Soils via Interpretable Machine Learning and Multi-Objective Optimization

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**ABSTRACT**

Anthropogenic heavy metal accumulation in arable soils constitutes a critical bottleneck for global food security and the "One Health" framework, necessitating sustainable remediation strategies that reconcile pollution control with agricultural productivity. Within the paradigm of safe utilization, organic amendments (OAs) are widely advocated for their dual capacity to sequester carbon and restore fertility; however, their deployment remains fraught with uncertainty due to the "double-edged" behavior of dissolved organic matter, which can inadvertently mobilize toxic metals under specific edaphic conditions. Conventional heuristic approaches, limited by linear assumptions, are insufficient to navigate the complex, non-linear trade-offs between remediation efficacy, yield enhancement, and secondary environmental risks across heterogeneous landscapes. To bridge this gap, this study develops a precision decision-support framework by synthesizing multi-decadal bibliometric data (1995–2025) into an optimized ensemble machine learning architecture. We successfully modeled the dynamic heterogeneity governing soil-OA interactions, employing SHAP (SHapley Additive exPlanations) to quantitatively decouple the mechanistic tipping points between metal immobilization and activation. Furthermore, the NSGA-III algorithm was deployed to resolve high-dimensional conflicts, generating a Pareto-optimal frontier of non-dominated solutions. These generalized results identify site-specific OA regimes that strictly constrain mobilization risks while maximizing ecological benefits, effectively advancing remediation strategies from empirical trial-and-error to data-driven precision management. Ultimately, this framework provides scientific leverage for digital soil governance, enabling policymakers to design spatially explicit incentive mechanisms that harmonize soil carbon sequestration goals with stringent food safety standards in sustainable agroecosystems.

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# An Integrated Practice and Model Building Based on the "Bio-Vitality Cultivation Method"

**Li Miaoxian,zhong Haiying, Wu Jiaqiang,**

## ABSTRACT

Soil health is the cornerstone of sustainable agricultural development. Addressing the degradation of soil ecological functions in China caused by high-input farming models requires the effective translation and widespread dissemination of soil science knowledge into practical technologies. This paper takes the "Bio-Vitality Cultivation Method" implemented by Just Agrotech Co., Ltd. as a case study. It systematically analyzes how this method transforms principles of soil microbiology and ecology into a core technological system for "targeted activation" of indigenous functional microbial communities. The study focuses on how this system is applied to soil ecological restoration through a closed-loop "diagnosis-activation-management" pathway and constructs a three-dimensional knowledge dissemination and agricultural technology extension model integrating "R&D, service, and science popularization." Practical data indicate that this system can reduce chemical fertilizer and pesticide use by 10%-50% while enhancing soil biological activity, improving crop quality, and significantly increasing farmers' income. This research provides a practical model for the application and effective dissemination of soil health knowledge, combining technological innovation, service empowerment, and educational outreach, offering valuable insights for promoting the green transformation of agriculture.

Keywords: Soil health; Knowledge translation; Microbial ecology; Technology dissemination; Input reduction and efficiency increase; Agricultural extension

Introduction

Soil degradation has become a core obstacle to global sustainable agricultural development, often rooted in the neglect of soil ecosystem complexity and the disconnection between soil management knowledge and its application. While ensuring food security, Chinese agriculture faces severe challenges such as soil compaction, loss of biodiversity, and disruption of nutrient cycling due to long-term reliance on chemical inputs. Addressing this dilemma requires not only advanced soil science knowledge but, more critically, the systematic translation of this knowledge into practical technologies that farmers can "understand, use, and see results from," and the achievement of large-scale, efficient dissemination and adoption.

The "Bio-Vitality Cultivation Method" is an integrated practical system developed in this context. It is not merely the application of a single technology but a comprehensive process that applies theories of soil microbial ecology and plant nutrition throughout problem diagnosis, technological product development, field service, and agricultural extension. This paper aims to systematically review and academically evaluate this system from the two dimensions of knowledge application and dissemination practice, to provide a replicable pathway for the scientification and popularization of soil health management.

1. Application and Translation of Soil Science Knowledge: From Theory to Targeted Technology

Effective knowledge application begins with accurately grasping core scientific issues and technological innovation. The application logic of the "Bio-Vitality Cultivation Method" reflects a deep understanding and engineering translation of the ecological concept that "soil is a living system."

(1). Scientific Basis of Application: A Paradigm Shift from "Addition" to "Activation"

This system departs from conventional approaches that simply add exogenous microbial agents or inert organic matter to soil. Instead, it is based on the principles of "resource regulation" and "competitive exclusion" in microbial ecology. Its core scientific understanding is that healthy soil itself harbors a rich gene pool of beneficial microorganisms (indigenous microbes), whose activity is constrained by the supply of energy (carbon sources) and nutrients. Therefore, the focus of technological application is not on "introducing external aid" but on targeted activation of existing, locally adapted beneficial functional microbial communities (e.g., phosphate-solubilizing bacteria, nitrogen-fixing bacteria, biocontrol agents) by providing readily available, high-quality organic carbon sources and metabolic stimulants (such as specific oligosaccharides and peptides). This aims to restore the soil's inherent functions of nutrient transformation, disease suppression, and structural stability.

(2). Development of Technological Products: The Vehicle for Materializing Knowledge

To realize the "activation" concept, two key products have been developed as the vehicle for materializing knowledge.

- Stronggreen®: Focuses on providing basic carbon sources and nutrition. Its highly active organic matter and small-molecule organic compounds provide the "food" foundation for the proliferation of indigenous microorganisms, aligning with the principle in soil biochemistry that energy drives microbial community succession.
- Enzyaetiver®: Focuses on providing metabolic signals and stimulation. Rich in various microbial metabolites, it aims to mimic root-microbe dialogue in natural ecosystems, targeting the awakening of specific beneficial microbial communities in the rhizosphere. This reflects the deep application of knowledge concerning microbial quorum sensing and the ecological functions of root exudates.

The iteration from the first to the second-generation product reflects the deepening of applied knowledge from "improving the soil environment" to "precisely regulating microbial functions."

2. Technology Dissemination and Agricultural Service Practice: Building Bridges for Knowledge Implementation

The value of advanced knowledge and applied technology cannot be realized unless effectively communicated to end-users. The Just system constructs a multi-level, interactive knowledge dissemination and agricultural service system.

(1). Closed-loop Technical Service: Embedding Knowledge into Management Decisions

The system establishes a standardized agricultural service closed-loop of "detection-diagnosis-prescription-tracking-filing." This is not merely service provision but a continuous process of knowledge infusion and feedback learning.

- Scientific Diagnosis First: Relies on professional laboratories for soil health assessments, translating the ABSTRACT notion of "poor soil" into quantifiable indicator problems—the first step in scientific understanding.
- Customized Solutions and Explanation: Crop therapists develop personalized plans based on diagnostic results, considering local crop and climatic conditions, and explain the underlying principles to farmers (e.g., "why activate bacteria rather than fungi at this stage"). This foster understanding of both the "how" and the "why."
- Visualization of Effects and Data Feedback: Field demonstrations and sensor data displays make results "visible." Simultaneously, collected application data feeds back into technology optimization, forming an iterative cycle of "practice-data-knowledge."

(2). Multi-dimensional Science Popularization and Extension: Reaching, Educating, and Influencing

Employing differentiated communication strategies for different audiences, a three-dimensional science popularization network is built.

- For Growers: Experiential and Participatory Communication. Offline experience stations, field observation meetings, and on-site training create immersive learning environments, using local success stories to change entrenched mindsets and shift from "passive acceptance" to "active inquiry."
- For Industry Channels: Empowerment-based Co-construction Communication. Empowers distributors and retailers with technical knowledge, transforming them from mere product sellers into localized technical service nodes, expanding the coverage radius and trustworthiness of knowledge dissemination.
- For the Public and Academia: Authoritative and Digital Communication. Collaborations with experts and media enhance the system's credibility. Digital tools like short videos, live streams, and agricultural service apps break through spatial and temporal constraints, making knowledge dissemination more dynamic and accessible.

3. Evaluation of Practical Outcomes: Demonstrating the Value of Knowledge Application and Dissemination

The effectiveness of this integrated system is the ultimate test of the success of knowledge translation and dissemination.

- Improvement in Soil Ecological Indicators: Post-application increases in soil available calcium/phosphorus (32%-50%) demonstrate the restoration of nutrient cycling functions. The alleviation of continuous cropping obstacles and reduction in soil-borne diseases confirm the beneficial regulation of microbial community structure.
- Enhancement of Agricultural Production Benefits: Data such as 10%-50% reduction in chemical fertilizers and pesticides, average crop yield increase of 25%, and income increase of 500-15,000 RMB per mu directly reflect the economic feasibility of the technology application. This serves as the most potent driver for the widespread dissemination of the knowledge.
- Expansion of Knowledge Dissemination Scope: Annual training exceeding 15,000 person-times, coverage of over 30 million mu of crops, and the establishment of hundreds of service terminals and demonstration sites signify that this knowledge system and technical solution have gained extensive market validation and user acceptance.

4. Discussion and Implications: Rethinking the Dissemination System for Soil Health Knowledge

The practice of the "Bio-Vitality Cultivation Method" offers the following insights for the application and dissemination of soil health knowledge:

1. Knowledge Translation Requires Systems Thinking: Effective technology is not an isolated point but a complete chain from scientific principle to product to usage protocol. The soil must be treated as a system, requiring systemic solutions.
2. Technical Service is the Core Dissemination Channel: In agriculture, face-to-face, problem-solving technical service is far more effective than one-way information delivery. Agricultural technicians (therapists) are crucial "knowledge translators" and trust bridges.
3. Economic Benefit is the Foundation of Dissemination: All scientific knowledge and technological dissemination must ultimately create perceptible value (especially economic returns) for the user. Successful dissemination models inherently incorporate a clear path to helping farmers improve quality and efficiency.
4. Digital Tools Amplify Dissemination Efficacy: Combining traditional offline services with digital tools (digitized detection data, online solutions, multimedia communication) can significantly enhance the precision, efficiency, and reach of knowledge transfer.

Conclusion

This study, through the analysis of the "Bio-Vitality Cultivation Method" case, demonstrates that promoting soil health management hinges on the organic integration of effective translation of scientific knowledge into application and widespread dissemination through innovative models**. This system, with "targeted activation of soil biological vitality" as its core scientific application, successfully translates specialized knowledge like soil microbial ecology into actionable management practices for farmers by constructing a complementary dissemination network of "closed-loop agricultural service" and "multi-dimensional science popularization." It has achieved significant ecological and economic benefits. This integrated paradigm of "knowledge-technology-service-dissemination" provides a scientifically grounded and practical References for the current agricultural green transformation centered on soil health.

# From Soil Healing to System Thinking: Repositioning Sustainability through Nature's Logic

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**ABSTRACT**

Modern sustainability frameworks often rely on comparisons with degraded environmental baselines to assess progress. While such benchmarks offer visible signs of improvement, they may obscure a deeper truth: we are still measuring success against broken systems. This presentation argues that truly regenerative sustainability cannot emerge from anthropocentric metrics, but must instead align with the self-organizing, cyclical logic of nature. Soil should be understood not merely as a medium for productivity, but as a living entity whose vitality depends on systemic balance, energy flow, and feedback loops. We propose three key shifts: from intervention to alignment, from symptoms to systems, and from static goals to dynamic coherence. We also highlight early efforts to construct AI-assisted ecological References models capable of simulating nature-based baselines. These models help quantify how far current land-use practices deviate from ecological resilience, offering a more accurate compass for long-term sustainability.

Black soil (Mollisol), with its high fertility and rapid degradation under pressure, offers a symbolic and practical case. Through this lens, the report invites the global soil and water conservation community to expand sustainability science: not only as a technological challenge, but as a cross-cultural and philosophical undertaking rooted in our relationship with land. By listening to the land—not just acting upon it—we may rediscover a regenerative path for both ecosystems and the scientific paradigms that guide us.

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# Soil and Life in Bayinbuluk

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**ABSTRACT**

Soil serves as the foundation of Earth's life-support systems, underpinning ecosystem functions while profoundly influencing the sustainable development of human civilizations and cultural identity. We will introduce the geographical and ecological context, soil formation factors, microbial diversity, ecosystem services functions, and patterns revealed through our scientific research regarding the Bayinbuluk alpine grassland (wetland) ecosystem in Xinjiang, China. Furthermore, we explore the critical role of soil science in revealing ecological resilience, supporting environmental conservation, and fostering cross-cultural understanding. In 2013, Bayinbuluk alpine wetland was inscribed as part of the "Xinjiang Tianshan" serial World Heritage property and listed as a UNESCO World Natural Heritage site.

The alpine meadow soil of Bayinbuluk is the product of long-term interactions between climate, topography, and living organisms. Its unique grass felt layer structure, rich microbial communities, and diverse plant-animal networks collectively form an efficient system for water conservation and carbon storage. Soil not only provides the habitat for local rare species such as the black-necked crane and swan but also carries the material heritage of herder cultures and ecological wisdom.

Globally, however, soils face multiple threats including degradation, desertification, and loss of organic matter. The Bayinbuluk case demonstrates that overgrazing and climate change pose severe challenges to its soil health. Through conservation practices such as scientific rotational grazing, soil restoration techniques, and public education, we can not only restore the land's vitality but also preserve place-based knowledge systems intertwined with the land, promoting both ecological and cultural sustainability.

From dirt to destiny—indeed, from the dirt of Bayanbuluk to the intertwined fates they sustain, supporting the lives of plants, animals, and human communities alike. Communicating soil science means recognizing soil as a living bridge between nature and civilization. Across regions, soil embodies place-based memory, ecological wisdom, and cultural heritage. Through science outreach, data sharing, and cross-cultural dialogue, we can deepen public understanding, and advance "Global Community of Shared Future" that healthy soil sustains all destinies—ecological, social, and cultural.

Keywords: Soil science; Bayinbuluk Alpine wetland; Sustainable development; Cultural understanding; Ecological conservation

# "Fertile Land with Childlike Heart"—Science Popularization Action of Little Guardians for Soil Protection

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## ABSTRACT

Heavy metal contamination in soil is a major environmental issue of great concern to society, and its coping mechanism is also a significant national strategic requirement. The public, especially primary school students, urgently need an accurate understanding of the causes, impacts, and control measures of soil heavy metal pollution. However, current geoscience-related popular science activities seldom cover this topic. Based on the organic integration of geoscientific knowledge and primary school science education, this study uses the primary school as a practice platform. Drawing on the experience in geoscience popularization, the study sets three research dimensions at different levels: "Cognitive Construction: Establishing a Scientific Thinking Paradigm," "Practical Innovation: Building New Forms of Science Popularization," and "Value Shaping: Cultivating an Ecological Civilization Mindset." It guides students to deeply understand the relevant knowledge and objective realities of soil heavy metal pollution, learn about the specific implementation paths and operational methods for remediation, and enhance the awareness of soil environmental protection as well as the depth and breadth of popularizing dialectical views on development in primary schools. The study's implementation will help strengthen the connection between the scientific community and the public and enhance society's understanding of basic research.

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# From Soil to Screen: Storytelling and Digital Media to Boost Soil Literacy

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**ABSTRACT**

From Soil to Screen: Storytelling and Digital Media to Boost Soil Literacy

Soils are fundamental to life on Earth, yet they remain largely invisible and poorly understood by the general public. Since not many schools include soil in their curriculum, most people lack a knowledge framework, a perception and terminology for soils; they are soil illiterate. People that have no education or prior knowledge in soils need to be introduced to it to be able to engage in it and appreciate it. To foster awareness, soils must be introduced in ways that connect with everyday experiences and stimulate curiosity—storytelling offers a powerful approach.

The World Soil Museum serves as an educational hub for researchers, students, and policymakers to learn about soil diversity, functions, and significance of soils. The showcase of the museum are the displays of soil monoliths—undisturbed vertical profiles that reveal natural layering, color, and structure and interactive exhibits. Storytelling is used in guided tours to bring people closer to soils in a way that it inspires and is more easily remembered so that it will be passed on in communication between people. They stick to the mind as they link with perception and understanding of the public on topics such as people, history, land management, food security, and climate change.

To increase impact, decrease the dependency on human guidance and to reach people that are unable to visit the World Soil Museum in the Netherlands, we have developed digital tools that provide access to the stories, information and collections of the World Soil Museum so that anyone with an internet connected device can be exposed to the soils of the world, their stories and their functions.

In 2014 the World Soil Museum of ISRIC launched a virtual soil museum that allowed online visitors to walk through the museum. At the same time collection searchers were developed for online visitors that facilitates access to the whole collection of the museum (≈1000 soil profiles from 75 countries) with full access to the data and high resolution image of the soil.

ISRIC has developed, within the framework of the EU-funded Curiosoil project for enhancing soil literacy, an app that captures the soil stories of the museum on various themes and provides access to the scientific information of the museum. The app is accessible on multiple digital media and screens and can be used both inside and outside of the museum. It contains quizzes, videos, audio-guide and textual information. It stimulates curiosity driven exploration of soil information and stories. The app differentiates the content for children and adults and is multilingual. In addition the World Soil Museum launches a new website that contains educational content for pupils and students and provides exercises and modules for teachers to use, with self-guiding instructions, with school groups.

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# Symphony of Biological Vitality

**Jiaqiang Wu, Zhuomin Zheng, Miaoxian Li, Chunchan Liang, Xiaohong Zheng**

## ABSTRACT

Symphony of Biological Vitality* is a stage play created by Guangdong Just Agro-Tech Co., Ltd. Through the personified interactions between soil organisms, crops, and farmers, this play vividly depicts the destruction and restoration of soil ecology in traditional agricultural production: It advocates for an ecologically friendly, scientifically sustainable approach to agriculture, emphasizing respect for natural laws and protection of soil biodiversity, aiming to achieve crop health, food safety, and agricultural sustainability by restoring soil vitality.
The script progresses through three stages:
1. Revealing the Problem: Excessive human interventions such as the overuse of chemical fertilizers, pesticides, and mechanical tillage disrupt the original biological balance of the soil, leading to microbial exodus, soil compaction, crop sub-health, and frequent diseases.
2. Proposing Solutions: Through the technical character "Jace," scientific diagnosis and ecological restoration methods are introduced, including the use of organic compost, small-molecule organic carbon, and biological activators, to rebuild the soil biological community and its functions.
3. Envisioning the Future: Promoting natural farming methods like cover cropping and mulching to restore soil vitality, ultimately achieving healthy crop growth and sweet fruits, echoing the vision of "striving for soil health, crop health, and human health."
Using humorous and vivid performances, the entire play calls on agricultural producers to "hear the voice of the soil and life," shifting towards a planting method that follows nature's way and conforms to ecology. This ensures yield while achieving harmonious coexistence between people and the land.
Keywords: Biological Vitality, Soil Vitality, Soil Health, Ecological Planting, Biological Activation, Bioremediation

Plot Content
1. The pristine ecological scene of soil, with various organisms cooperating and sharing food.
Narrator: The soil organisms in the virgin forest live and work in peace and contentment, leisurely and carefree, while the towering trees in the forest grow with deep roots and lush foliage. Suddenly, a strong wind blows, and a tree shudders. (All characters move about leisurely.)
Crop: This little wind and wave are nothing! Just shedding a few leaves, perfect to reward my brothers!
(A bacterium is dozing off/slacking, gets woken up by falling leaves.) Everyone starts bustling, discussing how to divide the work.
Bacillus: Brothers and sisters, we have a task. This piece of food is a bit big; we need more hands.
Filamentous Fungus: Coming, coming! (Extends hyphae.) I'll cut this giant into smaller pieces.
Nitrogen-fixing Bacteria: This carbon suits me perfectly. Local produce really does taste better.
Actinomycetes: How can you have something good without me! Found a great spot, quite comfortable here, dry and breezy. (Hides under a leaf.)
Earthworm: Let me take this back to nibble on slowly.
(Microbial-mineralized nutrients are thrown towards the tree base (basket). Nitrogen-fixing bacteria, after consuming leaves, reduce nitrogen gas into nitrogen and share it with the tree and other little companions.)
Crop: My meals this month are so abundant! Here, here, I'll also give you more sugars. Everyone has worked hard.
Microorganisms (together): 3, 2, 1, thank you, top supporter!
#2. Human intervention gradually begins to deplete and damage the soil. (The farmer cannot hear the tree's dialogue or the voices of the organisms.)
Narrator: People begin to enter this land for production, domesticating fruit trees.
Farmer: (Holding a compass) This is truly a treasure land! These trees are growing so well! Let me add some high-tech magic to make you grow even faster! (The farmer scatters compound fertilizer (chips and cola).)
Narrator: In pursuit of high yield, the farmer aggressively applies compound fertilizer. The crop grows wildly under the influence of massive nutritional fast food.
Crop: Yo-ho, these chips and cola are great! I'm getting fatter and fatter！ (being spoon-fed)
Farmer: (Legs crossed) Looks like trading five acres for a luxury car isn't just a dream！
Bacillus: Eating so well, seems you don't need me anymore. Well, I'm leaving then!
Nitrogen-fixing Bacteria: Brothers, the soil nutrients are so abundant; we can slack off a bit! (Throw away their function tags, lie down lazily near the roots, creating a chaotic scene of disarray.)
Narrator: With excessive nutrient elements added, the microorganisms think the big tree no longer needs their help. They all start slacking off.
Farmer: This high-tech magic is great! A bit more fertilizer, go all out, I'm going to get rich!
Crop: Boss, I can't eat anymore! I feel like I have indigestion. Why can't he hear me?
Narrator: The farmer doesn't know his crop is already over-nourished. He continues to apply fertilizer frantically. He not only wastes a lot of nutrients, causing an imbalance in soil nutrition leading to spindly growth, bloating, and "three highs" (metabolic issues) in the crop, but also breaks the soil's ecological balance, causing the soil microorganisms to flee, losing many free laborers! One wonders if he will regret it when he learns the truth.
#3. Microorganisms complain bitterly and begin to flee. Pathogenic bacteria gain the upper hand.
Actinomycetes: Sigh, working for such a boss is really no good!
Crop: Really sorry I couldn't provide a better environment for you. I couldn't help it either! Afraid I wouldn't have enough to eat, he just kept adding more, couldn't persuade him to stop (sighs)!
Farmer: Why isn't it growing even though I've applied so much fertilizer lately? These weeds must be stealing the tree's nutrients!
Crop: (Impatiently) That's because my roots are starting to rot. This soil is so salty and sour, like a pickling jar.
Narrator: On the nutritionally imbalanced soil, weeds begin to grow wildly!
Farmer: Weeds, what a nuisance! Now you'll see my true power! (sprays herbicide frantically)
Crop: Hey~ Boss, your high-tech magic is a bit overwhelming. My feet feel a bit hot.
Farmer: (Stomps foot, scratches the ground with hand) Why is the soil getting harder and harder? Let me get a rotary tiller to plow it.
Filamentous Fungus: Ahhh~ (Screams) It's over, it's over! I'm going to be shattered to pieces!
Earthworm: (Cut in half) Watch me perform the art of division!
(Pests and diseases start increasing.)
Pathogenic Bacteria: Hahaha (stands up), how come you're all out of commission! My chance has come! Full assault! (The pathogenic bacteria invade the entire soil environment.) You just fight each other! The more chaotic it is, the less anyone notices me (tiptoes across the stage, grabs the root's leg, and starts nibbling)!
Crop: Have mercy! My boss wants to trade for a luxury car!
Farmer: What's going on? Why are there so many pests and diseases? I just took a nap, what's happening? (Takes insecticide and fungicide to spray.)
Pathogenic Bacteria: Hmph, you think your mere fungicide can kill me? You know what they say: after three days apart, view a man with new eyes! (Upgrades equipment.) I can upgrade my combat power.
#4. Unstable weather ignites the fuse.
Narrator: Following this, two consecutive months of overcast and rainy weather add insult to injury. The tree begins to weaken, leaves droop, fruit drops. Farming the land becomes increasingly difficult, the trees grow worse and worse. What should we do about our future? The farmer constantly seeks solutions.
Off-stage voice (A childlike girl's voice rings out): Dad, Mom, will we still be able to eat healthy and delicious fruit in the future?
#5. Jace appears to diagnose the tree's condition.
Farmer (holds head, shakes it).
Then a soil technical specialist arrives.
Jace: I'm here!
Farmer: Welcome! Oh my, I used the best fertilizers and medicines, how did it end up like this?
Jace (Takes out instruments: EC meter, soil penetrometer, various test report boards): Saving the tree depends on the soil. We need to use scientific methods to see the current condition of the soil.
Jace: Look at this report, all nutrients are in excess ( shows EC meter).
Farmer: Isn't more nutrients a good thing? I even saved it for the tree, didn't keep it for myself.
Jace: (Very helplessly) You see, this is the common psychology of growers: excessive parental love, overdoing it.
Jace: You give a lot, but it can't eat that much.
Crop: (Concurs) Exactly, exactly! You understand me.
Then Jace checks the root condition (lifts the root's leg): The roots are peeling. Look, how can the tree roots absorb your nutrients like this? First stuffed full by fertilizer, then root damage. Damaged roots mean it can only starve. Starving makes it prone to sickness.
Farmer: So that's how it is.
Jace: (Takes out soil penetrometer; the penetrometer breaks.) This ground is so hard it broke my penetrometer.
Farmer: So I plowed the land several times. It's really hard work.
Jace: That doesn't solve the fundamental problem! We need to improve the biological vitality of the plot!
Jace: Where are your soil organisms? Why aren't they here? They may be small soldiers, but they are the great heroes of the soil, also the free laborers of the underground factory. How could you let them run away?
Farmer: I didn't chase them away either...
Jace: But every step you took destroyed their habitat, scared them all away! (Takes out a stethoscope for the farmer, lets the farmer hear the voices of the crop and organisms.)
Crop: I miss my little companions so much!
Jace to the organisms: Don't hide! All of you, come out and tell him!
Bacillus: When you were killing the pathogens, you took me out too!
Earthworm: When you were plowing, you broke me in half! (Shows broken leg.)
Fungus: Me too! My fungal network is all shattered!
Jace: Look, they are all injured like this. How can they work for your crop, how can they work for me?
Farmer: What you say seems to make sense.
Nitrogen-fixing Bacteria: (Pointing at a pressure gauge) And the work pressure is too high! I feel like I'm suffocating. In such a high-pressure environment, how can I work properly for you?
Filamentous Fungus: Look at this EC meter again. The value is so high, there are so many charged ions inside. Every time you water, my legs get shocked. I'm literally numb.
Farmer: It's all my fault for not hearing your voices earlier, causing such consequences.
Jace: (Everyone freezes.) Do you all think we should blame this farmer? (Pause.)
Jace: Actually, we farmers face four major pain points in the planting process: high fertilizer costs, soil degradation, unstable weather, and lack of professional planting knowledge. This farmer here has encountered these difficulties.
Jace to Farmer: Can't blame you entirely. It's caused by our common planting mindset. A very common problem is the "three highs and one low": high salt, high acid, high nutrition, low vitality.
Farmer: Sigh, I want to grow well too, just don't know how. No one ever properly taught me.
#6. Cultivation Theory and Product Intervention
Jace: Actually, there are free resources in nature itself. The deep-rooted, lush virgin forest also benefits from nature's gifts. So why don't we try using the power of nature?
Farmer: There are free resources?
Crop: Come on, brothers, let's show the boss the power of nature.
What is the sun above our heads? (Together: Photosynthesis, energy source!)
What are the carbon dioxide and nitrogen in the air? (Together: Carbon source, nitrogen source!)
How is our soil? (Together: Compacted!)
Is everyone breathing smoothly? (Together: No!)
Why? (Together: Lack of oxygen!)
Does everyone have enough food? (Together: No!)
What do you want to eat? (Together: Organic carbon!)
Jace (to Farmer): So, boss, what do you say we do?
Farmer: I don't know either.
Jace: You need to improve the soil first.
Farmer: How?
Jace: What does compacted soil lack? (Together: Carbon!)
Should it be small molecules or large molecules? (Together: Large molecules!)
Soil likes large carbon for improvement. So, on three, two, one... (Together: Show your talent!)
Organic Compost: I'm here! I'm the large molecule for soil improvement, rich in beneficial actinomycetes, best at improving the soil environment!
Farmer: You seem promising. So, once the soil is improved, what's the next step?
Jace: What is the main food source for our microorganisms? (Together: Organic matter!)
Can large molecule organic matter be absorbed directly? (Together: No, need small molecules!)
Is the conversion to small molecules a long process? (Together: Yes!)
What to do if they get hungry during the conversion? (Together: Water-soluble organic carbon!)
Microorganisms all love small-molecule organic carbon. So, on three, two, one... (Together: Show your talent!)
Strongeen® (Biological Oligosaccharides): Sweep away hunger, be yourself again! I am small-molecule organic carbon! (Distributes sugar.) Here, everyone gets some, none left out. I'll also call Deep Sea Essence to nourish the roots with vitality!
Farmer: Great! The microorganisms' food is also sorted!
Jace: (To microorganisms) Is having just food enough? (Together: No!) Need some stimulation!
Enzyativer®: (Biological Activator): Ignite energy, radiate vitality! Let me give you some "ambrosia," microorganisms, catch! (Scatters activator like a whisk.)
Nitrogen-fixing Bacteria picks up activator: Oh my, what kind of magical water is this? It tastes natural! So refreshing~
(Nitrogen-fixing bacteria busily work, converting nitrogen gas into nitrogen, passing nutrients to the roots and other bacteria.)
Fungus: Hey, my hyphae are growing back!
Enzyativer®:: I'm fermented from food-grade raw materials. Every drop is essence, the best is given to you.
Farmer: Real buyer testimonial! My luxury car hope is alive!
#7. Cover Cropping and Mulching
(Now, grass slowly starts growing.)
Grass: Wow, boss, you've restored this land?
Farmer: Of course! I have a soil doctor and a bunch of free laborers!
Grass: Guess what I want to do? Close your eyes, I'll give you a surprise. (Grass grows wildly.)
Grass: Okay, open them!
Farmer: Grass! (A type of plant) You really know how to make an entrance!
Farmer: Let me show you my power! (Takes out herbicide.)
Jace: Absolutely not! Grass roots can break soil compaction and also secrete organic carbon to feed your bacteria. When it grows tall enough, you cut it and return its nutrients to the field. Also, mulch is a good thing.
Crop: Weeds can also stimulate my root growth, making me focus more on work!
Grass: If you're going to reap my "grassroots revolution," say it quietly! Your plans are so obvious!
Farmer: You shut up! (Cuts it down in one swipe.)
**#8. Flourishing and Full of Vitality**
(The tree begins to regain vitality, flowers, bears fruit.)
Farmer: This whole year hasn't been easy. Who understands the hardship of farming? At the mercy of the weather, constantly worried, earning hard money walking a tightrope.
Jace: The planting end bears the greatest cycle and risk in the entire chain. What we can do is ensure every penny we invest is worthwhile. Use the power of nature wisely, follow nature's way, conform to nature, and nature will reward us with the sweetest fruits.
Child's Off-stage Voice: Dad, Mom, will we still be able to eat healthy and delicious fruit in the future? (Repeats once, echoing the earlier part.)
Narrator: Of course you will! We are all engaged in the cause for soil health, crop health, and human health, striving for the sustainable development of soil and crops, all so that you can eat safe agricultural products. You, like this tree, will grow up healthy and strong under the care of our Biological Vitality Cultivation Method.
All characters sway and wave their hands, presenting a scene of unity. The MV for "Our Soil" plays.
The End!

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# Past, Present and Perspective of Soil Science Communication in China

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## ABSTRACT

**1. Early soil science popularization activities,**
China's research on soil as a science should have started with the Soil Research Office of the Central Geological Survey founded in 1930. The activities of soil science communication are relatively early. China Soil Society decided to establish a working group on popular science when it held its fourth member congress in Chengdu in 1979. After more than a year of preparation, it held its first working conference on popular science in Nanjing from November 23 to 26, 1981. Then, from June 27th to July 1st, 1983, the second meeting of the Chinese Soil Society was held in Changsha.
In the first conference on soil science popularization, Lin Putian, a representative of science popularization, has published more than 250 popular science articles in Hunan and national newspapers and periodicals. In addition, the national soil science popularization work has also taken scientific and educational films such as "red soil utilization improvement" and "phosphate fertilizer" and produced slides such as "crop malnutrition", which have promoted agricultural production. The book "Soil Knowledge" compiled by Nanjing Institute of Soil Science, Chinese Academy of Sciences, has issued nearly one million copies. And made some work plans, including: (1) compiling and publishing popular science works such as Soil in China and Application of Trace Elements in Agricultural Production;
(2) Make and distribute a set of slides of "Main Soil Types in China", and a series of popular science slides will be made and distributed according to regions or soil types in the future;
(3) Cooperate with Shanghai Science and Education Film Studio, first complete the science and education film of Boron Fertilizer, and then complete the science and education films of Zinc Fertilizer, Molybdenum Fertilizer and Manganese Fertilizer before 1985;
(4) Learn the form and experience of "Rural Service Desk" sponsored by Jiangsu Association for Science and Technology, and the soil societies of Jiangsu, Yunnan, Hebei, Liaoning and other provinces will cooperate with the popularization departments of provincial associations for science and technology to edit and publish short articles introducing the scientific and technological knowledge of soil and fertilizer for rural agricultural technicians;
(5) Decided to organize the compilation of a set of intermediate popular science books "Soil and Fertilizer Knowledge Series" to comprehensively and systematically introduce the knowledge of various branches of soil science;
(6) With the support of the Popularization Department of the National Association for Science and Technology, 1-2 sets of maps and cards on nutrient deficiency in soil and plants will be produced;
(7) In order to cultivate young people's interest in natural science, since 1982, a popular science summer camp for young people has been jointly organized in Shenyang by Zhongyin Soil Society, Liaoning Soil Society and Liaoning Botanical Society, and will be held once a year in different areas.
(8) In order to meet the convening of the fifth member congress of China Soil Society in 1983, it was decided to hold an exchange meeting on the experience of popular science work of China Soil Society before the convening of the congress in 1983.
The second conference on popular science held by China Soil Society was held as scheduled in 1983. There were 47 members of popular science committee and representatives of provincial societies. The conference exchanged experiences of popular science from all over the country, but the first popular science plan was not completed. At this session, new ideas were put forward, including:
(1). Before 1985, hold a class on soil science creation and soil scientific research photography technology; Seminar on popular science of metered fertilization.
(2) In order to review the achievements of soil science popularization, it was decided to edit and publish the National Collection of Excellent Works of Soil Science Popularization and 100 Cases of Soil Science and Technology Application Achievements, and it is planned to display the soil science popularization materials of various provinces at the fifth national congress of the Soil Society.
(3) The meeting further studied the issues related to the Soil Knowledge Series decided by the first meeting of popular science work, initially worked out the compilers of each volume, and decided to write the first draft before 1985, so as to be published as soon as possible.
(4) In order to strengthen the work of soil science popularization, the meeting asked the provincial and municipal societies to set up science popularization organizations as soon as possible, actively carry out the work of soil science popularization, and make contributions to agricultural modernization.
Unfortunately, the third conference on soil science popularization in 1985 was not held as scheduled, and the work of science popularization was interrupted afterwards.
Before 2018, China's scientific popularization worksheet was in technical training and technology promotion. For example, in 2018, the relevant departments of the Ministry of Agriculture carried out the third phase of national cultivated land quality evaluation technology and the first phase of national supplementary cultivated land quality acceptance evaluation technology training.
In addition, with the rise of self-media, some enthusiastic soil workers have launched Weibo, Blog and WeChat WeChat official account. For example, since 2012, Chen Nengchang has carried out soil science popularization activities in Weibo, and released more than 1,000 pieces of popular science information in one year, which attracted considerable attention. In 2013, Chen Nengchang was invited by a chair to make a video of Sick Land, which caused considerable repercussions.
In 2013, a piece of news, "The whereabouts of 10,000 tons of rice with excessive cadmium in Hunan flowing to the dining table in Guangdong became a mystery", aroused the concern of the whole society about food security and human health, and Chen Nengchang was invited by Hunan Provincial People's Congress to give a special report on popular science. In the following years, Dr. Chen Nengchang made over 200 popular science reports nationwide, covering all aspects of soil in China.
Following the Air Pollution Prevention Action Plan and the Water Pollution Prevention Action Plan, China launched the Soil Pollution Prevention Action Plan in 2015, updated the Soil Environmental Quality Standard in 2018 and promulgated the Soil Pollution Prevention Law in 2019. During this period, Dr. Chen Nengchang participated in the consultation of the above three aspects for many times, which played a driving role.
In 2015, on the occasion of World Soil Day, "Silent Soil", the first large-scale domestic soil science book co-authored by Gong Zitong, Chen Hongzhao and Zhang Ganlin, was published in Science Press, which initiated the systematic dissemination of soil science in China, achieved a milestone breakthrough from technology transfer to cultural enlightenment with the narrative of integration of science and humanities, and reshaped the public and policy's understanding of soil with its international influence and long-term social value. The publication of Silent Soil can be said to be a milestone in the cause of soil science popularization in China.
On the other hand, at that time, WeChat official account attracted people's attention as a new way of communication. From January 20, 2014 to July 4, 2018, the WeChat WeChat official account Soil Watch launched by Chen Nengchang distributed 1,107 articles with 38,072 fans, Soil Home (March 26, 2018) and 67 articles with 2,766 fans, Environment and Health Watch (2008).

**2. Soil science popularization activities in recent years,**
On November 21, 2019, the new Science Popularization Committee of China Soil Society held a meeting in Guangzhou, which established the action of soil science popularization into campus, countryside and enterprises, and the communication of soil science has been greatly developed.
On World Soil Day in 2020, members of the Science Popularization Committee of the Chinese Soil Society launched 111 science popularization activities and marked them on the map of FAO.
In recent years, soil science popularization activities have the following characteristics:
1) The popular science activities of Zhu Yongguan, Zhang Fusuo and other academicians in national media and other media have produced great publicity effects. Many agriculture-related enterprises have also carried out various propaganda on soil science through the media, which has greatly improved people's attention and attention to soil;
2) During this period, many popular science books on soil were published, such as Living Soil (2023) edited by Zhu Yongguan, Soil: the Skin of the Earth-Telling the Story of Soil Science from Postal Culture (Science Press, 2021) edited by Yang Shunhua, and Cultivation and Practice of Healthy Soil translated by Chen Nengchang. and others.
3) The soil song "Our Soil" released in 2023 has been widely spread, which has effectively promoted the spread of soil science.
4) On the celebration day of World Soil Day in 2025, the opening ceremony of the first national soil science museum "Shishi Wansheng Soil Science Museum" was held in Shishi city, Fujian Province, which means that the communication of soil science in China has moved from official to folk, from urban to rural, and the first soil science museum will lay a solid foundation for the normalization, long-term and landing of soil science.
5) The Science Popularization Committee of China Soil Society will vigorously promote the construction of soil science popularization bases and further promote the dissemination of soil science.
6) China's first Law on Popularization of Science and Technology in People's Republic of China (PRC) escorted the dissemination of soil science.

**3. Future of soil science popularization in China.**
The relationship between soil and people is just like the relationship between fish and water. As the foundation of human survival and development, soil health profoundly affects the sustainable development of human beings.
In the future, in addition to actively carrying out your activities of popularizing soil science in campus, enterprise and countryside, China will do two things well.
1) Take the "Shishi Museum of Soil Science" as a template to promote the nationwide development of this model.
2) Strive to build more soil science popularization bases nationwide.
Let every Chinese realize the importance of soil, care for soil, protect soil, make soil healthy, and make Chinese civilization more brilliant!

# On Shishi Wanwusheng Soil Science Communication Hall

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**ABSTRACT**

Soil science is a small science that affects everyone's health. As the most complex multi-media and multi-interface substance, soil science is highly professional. Soil formation is slow, and the time scale is tens of millions. In the lifetime, human beings can't feel the influence of soil changes on human civilization and sustainable future, but the soil is also very fragile. Soil degradation such as soil pollution and soil acidification can be completed in a short time, and it affects the health of contemporary people.

Therefore, it is our duty as soil scientists to make everyone realize the importance of soil, and to protect and care for soil. The dissemination of soil knowledge cannot be deeply rooted in people's hearts after speeches, and it takes a long time for the public, especially farmers, to have enough knowledge of soil science.

To this end, we took the lead in setting up a non-profit organization “Shishi Soil Science Communication Hall” in Shishi City, Fujian Province, China, which aims to achieve the normalization, long-term and landing of soil science communication and make contributions to rural revitalization and soil protection in China.

At present, the content of the soil science museum has three parts.

The first part is to publicize the dedication of soil scientists and introduce the course and great achievements of famous scientists in studying soil.

The second part is to show the past lives of soil, and introduce the generation and evolution of soil on the earth in an easy-to-understand way; The relationship between major soil degradation events, soil health, soil degradation and human health and sustainable future!

The third part is the library, laboratory and dialect multimedia room, which can improve the local soil by training new professional farmers and play a demonstration role in building healthy soil.

In addition, we also have a lecture hall for soil science, inviting famous scholars at home and abroad to give lectures and exchange views.

Welcome soil scientists at home and abroad to visit our “Shishi Soil Science Communication Hall”!

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# Siliceous restrictive layer: a new soil constraint in Northeast China's Black Soil Region

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## ABSTRACT

In recent years, extensive soil surveys have revealed a unique silica-clay composite horizon—now identified as the *siliceous restrictive layer (Btq)*—that blankets vast areas of Northeast China's black soil region. Unlike the well-known *fragipan (Bx)* described in Soil Taxonomy—which features loam-dominated composition and yellow-brown prismatic structure—this newly discovered Btq layer stands out with its silt texture and distinctive bright brown granular structure. This layer acts as a "hidden barrier" to sustainable agriculture by limiting root penetration, reducing water infiltration, accelerating slope erosion, and threatening regional food security.

- **Key characteristics**

**a. Physical Properties**: Low organic carbon (<1.43%), moderate total nitrogen (<0.15%), elevated available phosphorus (<30.83 mg/kg), high bulk density (>1.31 g/cm³), and weakly acidic pH (6.08)

**b. Particle Size**: Silt-dominated composition (6.27–20.01%) with minor clay content

**c. Geochemistry**: Enriched $SiO_2$ (>63.41%), moderate Fe/Al ratios, high silicate activity factor (Saf > 2.97), and intermediate eluviation intensity

- **How is it formed?**

The layer forms through dual regulatory processes:

**a. Terrace-Hilly Regions**: Groundwater dynamics interact with biological cycling—periodic groundwater fluctuations drive silica mobilization, while plant roots and detrital recycling enhance silica accumulation

**b. Mountainous Regions**: Dominated by biogeochemical cycling—plant silica uptake and organic matter decomposition create localized enrichment zones

- **what is the spatial distribution pattern?**

Covering 8,137 km² across key agricultural cities (Jixi, Jilin, Tieling, Hulunbuir), this layer occurs at depths of 28.8–65.3 cm with thicknesses of 51.5–92.4 cm. Silica neoformation abundance ranges 18.5–29.6% with densities of 303–630 g/dm³.

- **Practical implications**

Understanding this layer's distribution, characteristics, and genesis provides critical tools for:

**a. Soil Management**: Targeted interventions to mitigate root penetration barriers and water movement restrictions

**b. Agricultural Sustainability**: Enhancing food production while reducing slope erosion risks

**c. Soil Taxonomy**: Refining classification criteria for Chinese Soil Taxonomy's basic units (soil series)

This discovery advances soil science by identifying a novel constraint layer type and establishing formation models that bridge hydrological, biological, and geochemical processes. The findings offer actionable frameworks for sustainable black soil region management and global soil classification systems.

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# Biochar-based fertilizers alter the ecological components of organic carbon in the soil aggregates of red soil tea gardens

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## ABSTRACT

Soil aggregate is an important indicator of soil structure and fertility in tea gardens. The stability of soil carbon pool is seriously affected by the problems of soil compaction and nutrient impoverishment in tea gardens in Guangxi.Mineral elements in red soil tea gardens, especially calcium, iron and aluminum, are closely related to changes in soil acidity and affect the stability of soil organic carbon and the formation of tea quality. Soil calcium-bonded organic carbon and iron-aluminum bonded organic carbon are organic mineral complexes with metal ions and metal oxides as bond Bridges respectively, and they have relatively high stability.A systematic assessment of the effects of applying biochar-based fertilizers in red soil tea gardens on the structural characteristics of calcium-bonded organic carbon and iron-aluminum bonded organic carbon in soil aggregates is conducive to reducing soil obstacles and enhancing productivity in intensive tea garden. In this study, a 40-year old Xishan tea garden in Guiping, Guangxi, located along the Tropic of Cancer, was selected as the research object. Three treatments [biochar-based fertilizer (BF), chemical fertilizer (F), and no fertilizer (CK)] were used for a field positioning test for two consecutive years to explore the structure and distribution pattern of calcium-bonded organic carbon and iron-aluminum bonded organic carbon in the red soil tea garden soil.

Evaluating the effects of biochar-based fertilizer application on the organic carbon structure characteristics and physical stability of soil aggregates in tea gardens can help to reduce soil barriers and improve productivity in intensive tea gardens. The results show that:The research results show that: (1) The application of biochar-based fertilizer increased the contents of Ca and Al in the tea garden soil. The Ca content of BF was 87.74% higher than that of CK, and the Al content of BF was 47.52% and 65.08% higher than that of CK and F respectively. (2) The application of biochar-based fertilizers reduced the content of calcium-bonded organic carbon (Ca-OC) in tea garden soil. The content of Ca-OC in the whole soil of BF decreased by 42.86% compared with CK. In the aggregates with particle size ranging from 0.25 to 2.00 mm, the content of Ca-OC in BF decreased by 75.41% and 63.41% respectively compared with CK and F. The proportion of total organic carbon in the whole soil Ca-OC of BF was 36.76% lower than that of CK. (3)The application of biochar-based fertilizer increased the content and contribution rate of Fe/Al-bound organic carbon (Fe/Al-OC) in the large aggregates of tea garden soil. In the aggregates with a particle size of >2.00 mm, the Fe/Al-OC content of BF was 39.66% higher than that of F, and the contribution rate of Fe/Al-OC (CRFe/Al-OC) of BF was 19.71% and 82.60% higher than that of CK and F, respectively. In the aggregates with a particle size of 0.25-2.00 mm, the Fe/Al-OC content of BF was 23.40% higher than that of CK, and the proportion of Fe/Al-OC in total organic carbon of BF was 26.30% higher than that of F. The application of biochar-based fertilizers is conducive to the optimal management and control of red soil tea gardens and the stability of carbon pools.

**KEY WORDS**

Calcium bond, Iron-aluminum bond organic carbon, Agglomerate, Carbon sequestration in tea gardens

**Acknowledgments**

Mineral elements in red soil tea gardens, especially calcium, iron and aluminum, are closely related to changes in soil acidity and affect the stability of soil organic carbon and the formation of tea quality. Soil calcium-bonded organic carbon and iron-aluminum bonded organic carbon are organic mineral complexes with metal ions and metal oxides as bond Bridges respectively, and they have relatively high stability.

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# Addressing the Pains of Chemical Agriculture with Traditional Farming Wisdom: The Practice of the Qinbang Farm Model

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## ABSTRACT

Soil degradation, heavy metal pollution, and biodiversity loss, stemming from chemical agriculture have resulted in the decline of agricultural ecosystem services.Ecological organic agriculture, as a production system that upholds soil, ecosystems, and human health, integrates economic development with environmental protection and resource utilization through human intervention. It establishes a symbiotic relationship between ecology and economy, achieving sustainable agricultural development[1]. As China's first 100ha whole-system organic ecological farm, Qinbang Farm adheres to biodynamic farming principles. For environmental restoration, it employs a composite fermentation technique using cattle manure and crop straw to produce multifunctional microbial inoculants as dynamic preparations, thereby rehabilitating and safeguarding the farm's cultivation environment. In soil nutrient and energy cycles, indigenous microbial organic fertilizers compensates for the deficiency of mineral fertilizers, enhancing soil nutrient retention and water-holding capacity. For pest control, a synergistic network of natural enemies and plant secondary metabolites replaces chemical pesticides, preserving farm biodiversity by transforming waste into cyclical production inputs. The farm pioneers a sustainable, closed-loop agricultural model. Over nearly two decades of chemical-free farming, the system achieves zero emissions. Soil organic matter rises from 0.6% to 4%, with over 100 earthworms per square meter. Rice yields exceed 9000 kg/ha, and laying hens maintain a production rate above 71%. This model provides a repeatable triad of microbial regulation-material cycling-ecological restoration formation for addressing agricultural non-point source pollution, holding significant practical value for the implementation of Circular Agriculture. Soil microorganisms, as sensitive bioindicators of soil health play crucial role in nutrient cycling, soil structure improvement, and pesticide degradation within the whole-region organic ecological farm model[2-7]. This study aims to investigate their practical value for the implementation of circular agriculture. Emphasis is placed on mining, constructing, and utilizing core microbiome information data from multiple microbial processes. It provides a scientific basis for predicting soil health levels[8-9] by targeting the use of microbial community profiles to enhance agricultural soil ecosystem functions, maintain soil health, and promote sustainable agricultural development.

**Keywords:** ecological organic agriculture,sustainable agricultural development,soil microorganisms

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# Soil aesthetics in the popularization of soil science

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**ABSTRACT**

Soil performs many essential functions in the biosphere, which are studied in detail by soil scientists. However, researchers rarely consider another key function of soil—the aesthetic one. A soil profile is not only a carrier of information but also a painting by Nature itself. Numerous complex chemical, biochemical, and physical processes act like brushes and paints, gradually creating different soil horizons with varied structures and colors. Soil scientists distinguish over 400 colors in soils. In painting, these are often referred to as "earth colors." They have been used since the first cave paintings and continue to be applied in modern artworks. Revealing the aesthetic function of soil is an important element in understanding and popularizing soil science, capable of sparking interest among schoolchildren and students.

In 2017, the idea emerged to create a popularization group at Lomonosov Moscow State University called SoilART, consisting of researchers and students. Its purpose is not only to study soils of the north but also to promote the ideas of aesthetic soil science. The mission of SoilART is to reveal the beauty of soil to a wide audience. Since then, numerous workshops have been conducted at various events, and their number continues to grow. We hold lessons on the aesthetics of soil science for different audiences, using our own original approach to representing images at the intersection of science and art.

The Faculty of Soil Science at Moscow State University hosts a permanent Science and Art exhibition.

Science: soil, its granulometric particles, structure, and soil formations.

Art: pigments, soil-based paints, dorodango (soil balls), installations.

The centerpiece is a panel depicting soil-forming factors. Now, soil science students, teachers, applicants, and guests can explore soil through the lens of Science & Art.

By revealing the aesthetic function of soil, we tell the story of soil, its composition, and structure. When demonstrating the diversity of soil colors and pigments, we explain their chemical and mineralogical composition. While creating dorodango, we discuss the physical properties of soil. Through "Natural Paintings"—beautiful soil monoliths—we identify traces of soil-forming processes and formations, and explain soil genesis. Art allows us to interact with soil on a sensory level. Vivid imagery helps attract people to soil science topics. Listeners captivated by the aesthetic side of soil come to our soil workshop to expand their knowledge.

Thus, the group's activities contribute to the scientific education of schoolchildren, applicants, students, and others, while also showing soil scientists the aesthetics of soils. Each seminar and workshop by the group is unique, as the program is tailored to the audience's needs and prior knowledge. Presenting soil aesthetically helps draw attention to soil genesis and the challenges of soil preservation.

# Performance: Open Hands

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**ABSTRACT**

The Performance began in the 60s, spread internationally,"art that refuses to settle", unrepeatable, actions carried out by the performer or recorded, spontaneous or scripted, answering: if we performatize a meeting, an excursion, a class, a conference, a soil communication? The objective is to generate a rupture for those who observe, to make the extraordinary appear, the difference that exists below the surface, we are unaware of its diversity, with amazement or not, in some spectators there is no strangeness, they already know its landscape. It is carried out in an agricultural high school in Santiago del Estero, Argentina, in the schoolyard, with soil samples of four soil profiles from the area in the corners, in the center a large white wooden square. The performer/s with images makes a tour of the local geoforms and each student takes a soil sample, places it in a container, adds water to make mud, plunges their hands into that material, experiments and then rests their hands on the square leaving that mud attached. He walks around the square, stops, looks at his hands, and the others, washes and starts again. Finally, the square is raised showing all the participants the work of "art made" with the different soils of the area. The scenic event builds on a network of individual and collective possibilities, in a union between, with a dilated scenic power, because it continues in space, in walking the territory, to mentally and fully appropriate the vitality and diversity of the relationship soil landscape.

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# Classifying Soils with Artificial Intelligence

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**ABSTRACT**

Artificial intelligence (AI) holds remarkable potential across multiple disciplines and is increasingly assisting soil scientists. In this work, we explore one of its applications in soil science: developing rapid and accessible methods for soil classification. We compared usability and workflow simplicity of the three following tools, ChatGPT -conversational AI- (OpenAI), NotebookLM -AI analysis assistant- (Google, 2025) and PartyRock -interactive AI- (Amazon Web Services, 2025) to classify soils according to the World References Base for Soil Resources (IUSS Working Group WRB, 2022). Each system was provided with data sets containing detailed field descriptions and laboratory analyses of soil profiles previously classified. The evaluation focused on the ability of each AI to identify diagnostic horizons and soil qualifiers correctly and deliver consistent classifications. Results showed that ChatGPT accuracy was highly prompt-dependent, which is limited by the expertise of the user, NotebookLM relied strongly on user-uploaded documents but was less prone to "hallucinations", while PartyRock offered superior visualization and user interaction yet required more guidance and time to build and interact with the app to get a reasonable output. None of the AI tools analyzed delivered fully consistent results as repeated runs with the same dataset led to minor variations in the output, underscoring the difficulties in ensuring reproducibility. Nevertheless, these tools demonstrated clear potential for use in teaching soil classification and for supporting preliminary mapping or field decision-making. This study highlights the promise of AI as a complementary aid in generating rapid, reproducible, and transparent classifications, although expert oversight remains essential for final validation.

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# Artificial Intelligence Assisted Soil Description and Inference

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**ABSTRACT**

Detailed soil profile descriptions are essential for site characterisation, soil mapping, pedological studies, soil–landscape modelling, and classification. Soil profile descriptions are also useful for monitoring soil change and the impacts of management practices on the soil. However, delineation and horizon identification can vary among observers, leading to inconsistencies in soil data interpretation. Moreover, soil profile descriptions remain challenging to derive from proximal and remote sensing technologies, including spectroscopy, due to their shallow sampling depth and limited ability to capture the structural and morphological complexity of soil horizons. This study explores the potential of artificial intelligence (AI) to assist in soil profile description and inference. Using two case studies from Turkey and Australia, we tested whether AI could be trained to predict and refine soil profile descriptions.

The study was structured in three stages for five soil profiles from each area. First, ChatGPT was prompted as a soil surveyor to describe and classify soil profiles (USDA, WRB, and Australian Soil Classification) from uploaded profile images. Second, textual profile descriptions were provided for AI-based correction and estimation of horizon properties, including clay content, organic carbon (OC), calcium carbonate ($CaCO_3$), and available water capacity (AWC). Third, laboratory data was introduced to refine estimates and calculate OC and inorganic carbon stocks and AWC. Subsequently, new profiles similar to the original five were used to evaluate whether the AI could transfer knowledge from previous examples to improve predictions.

The study demonstrates a workflow for evaluating AI-assisted soil description and inference, providing insights into the potential ofAI as tools for supporting soil survey and classification across diverse environments. Such capabilities can enhance the consistency and interpretability of soil profile data and facilitate their integration into digital soil mapping and comprehensive soil assessments.

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# Mixed reality for soils monoliths: an example from the National Museum of Soils of Mexico

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**ABSTRACT**

Digital tools are transforming how soil science is documented, taught, and disseminated. Following the logic of Industry 5.0, digitalization and immersive visualization (AR/VR) combine with mobile devices and lightweight data streams to bring edaphological heritage to diverse audiences. Soil monoliths preserve the morphology and structure of representative profiles; however, their consultation is usually in person.

This work presents a web platform integrating interactive 3D models and augmented reality (AR) experiences of 12 monoliths from Mexico's National Soil Museum, located at the Colegio de Postgraduados, Campus Montecillo (Texcoco, Mexico). The proposal expands access for students, teachers, and specialized audiences to interact with soil heritage without time or location barriers.

Digitalization was performed using photogrammetry, capturing a series of multi-view images in a controlled environment. Preprocessing reconstructed point clouds and meshes; texturing was applied for export in standard formats using photogrammetry software. Subsequently, the models were normalized in open-source 3D mesh editing software (unifying scale, orientation, and position), and texture touch-ups were made to improve color and lighting continuity. Likewise, controlled decimation was applied to reduce the polygon count without losing relevant features, generating smaller GLB files that favor fast loading times and smooth AR performance without overloading devices.

The site implementation was built with Angular, TypeScript, SCSS, and HTML, prioritizing performance and ease of use. To offer AR without requiring app installation, the platform invokes Scene Viewer (Android) and Quick Look (iOS) directly from the web. Thus, the user can place the monolith to scale in their environment, rotate it, and zoom in on details like structure, aggregates, or horizon boundaries. On desktops, the 3D viewer allows fluid exploration with simple controls. Each model includes essential metadata, and a uniform 3D "table-like" base was designed to standardize presentation.

To assess educational utility, a semi-structured survey was administered to students. The response was positive; participants noted that interacting with 3D models improves morphological comprehension, encourages autonomous study, and is more motivating than static resources. They also highlighted 24/7 access from personal devices and the ability to "bring" the monolith into the classroom or home as practical support for classes and labs.

Overall, the project provides a reproducible and affordable workflow (sensor + photogrammetry + processing + web AR) that democratizes access to soil collections, reduces handling risks for physical specimens, and opens opportunities for teaching, outreach, and digital conservation. Future work includes expanding the collection and languages, implementing usage analytics, and linking each model to laboratory data and geospatial context.

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# Technology in Soil Science Education in the 21st Century: Web, Software, and Apps for Generation Z

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**ABSTRACT**

Soil science has been trending since the beginning of the Decade of Soils in 2015, with the global population seeking to understand the importance of soils. In the educational sphere, the digital native generation, known as Generation Z, demands new learning methods using social media. Therefore, it is urgent and necessary to generate soil science content for this new audience, as traditional soil science education has failed to engage young people due to a lack of access to audiovisuals appealing to scientific information, a lack of practical applications, and outdated teaching methods. The objective of this work was to create and develop a virtual museum of Mexican soil geography, providing accessible digital information for all audiences, and to acquire scientific knowledge in soil science. This effort aimed to modernize soil science education in Mexico and globally.

In 2021, a website called Virtual Museum of Soil Geography of Mexico (https://museosuelos.ciga.unam.mx/) was created with the intention of: a) organizing the YouTube channel videos by topic; b) organizing blog posts by topic; c) showcasing the technology developed (software and apps); d) creating a repository of soil maps of Mexico using geopedological, digital, and ethnopedological approaches, as well as digital maps of heavy metals in 14 Mexican cities; e) creating a museum blog to disseminate ideas about soil mapping and environmental functions; and f) creating a module for the automated evaluation of soil profiles in the state of Michoacán with an agricultural focus. The story begins in 2013 with the creation of the YouTube channel Soils, Environment, and More, which now boasts 309 videos, 2,716 subscribers, and nearly half a million views (508.5k views and 23.7k plays). That same year, the first blog, also named "Soil Scientists, Pedometricians, and Soil Lovers," was launched and currently features 234 posts and 143.3k reads. Also in 2013, the Facebook group "Soil Scientists, Pedologists, Pedometricians, and Soil Lovers" was created, which has almost 14.2k members and over 35k views per month.

The website for the "Virtual Museum of Soil Geography of Mexico" now features 328 videos, over 315 blog posts, geopedological and pedometric maps, and technology developed for the study and application of soil science. The museum's website has received over 94.4k visits worldwide, mainly from North America, Europe and Asia, in that order, but with intermittent visits from Oceania and Latin America. The website is an international benchmark for teaching soil science.

**Acknowledgments**

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# Agricultural land assessment using a web portal in Michoacán, Mexico

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**ABSTRACT**

Michoacán is a state of national importance in fruit production, boasting, for example, 240,000 hectares of avocado orchards, thousands of hectares of lemon groves, and berries such as blueberries and raspberries, among others. However, agricultural activities are responsible for environmental degradation, and 40,000 hectares of agricultural land are lost annually due to poor land selection. The objective of this work was to design and develop an Automated Land Evaluation System (ALES) for Michoacán, Mexico. Information on topography, climate, and soils was analyzed to establish References intervals for evaluating land and soil profiles. The evaluations were automated in a web module developed using a combination of technologies. For example, the user interface was built with HTML, CSS, and JavaScript, complemented by jQuery to facilitate application programming interface manipulation and enhance interactivity. The Python framework Django was used for the backend, providing a secure structure for web application development. PostgreSQL was used to manage the relational database. The web module generates an agricultural site assessment based on topography and climate. It also generates a soil profile assessment by horizon, allowing for the identification of horizons with agricultural limitations. This efficient system enables a precise and rapid evaluation of the information. The assessment can be performed directly or through an external form embedded on the website. The system classifies the terrain and soil profile variables into five classes (very low, low, medium, high, and very high suitability), coloring the profile horizons and terrain classes from green to red, corresponding to the suitability levels from very low to high. This simple way of expressing the assessment will facilitate understanding for agricultural technicians training in the state of Michoacán through agricultural preparatory schools, as well as for the work of technicians in the federal "Sowing Life" program. The assessment report can be exported to an Excel file. The web portal and the agricultural soil profile assessment method have been specifically designed and developed for the state of Michoacán, Mexico. The primary soil groups in this region include Andosols, Cambisols, Luvisols, Vertisols, Leptosols, and Regosols. Therefore, it is not necessary to include characteristics in the assessment model that pertain to soils that do not exist in this state. This method of evaluating soil profiles is beneficial for assessing all the government's pedological information, which comprises more than 500 soil profiles. The website is in the Virtual Museum of Soil Geography of Mexico (https://museosuelos.ciga.unam.mx/) of the Centro de Investigación en Geografía Ambiental de la Universidad Nacional Autónoma de México.

**Acknowledgments**

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# The Algorithmic Lens: Unraveling Soil Structure with Artificial Intelligence

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**ABSTRACT**

The discipline of soil science is undergoing a profound transformation, shifting from static, destructive measurements to continuous, high-throughput data acquisition. However, the resulting volume and complexity of multi-dimensional data have outpaced traditional analytical frameworks, creating a critical need for advanced computational tools. This review examines the emergence of Artificial Intelligence (AI) as an essential "algorithmic lens" for unraveling the complexity of soil structure across scales. We explore how Deep Learning, particularly Convolutional Neural Networks (CNNs), is revolutionizing micro-scale characterization by automating the segmentation of X-ray Computed Tomography (CT) imagery with high fidelity. At the macro-scale, we discuss the use of Machine Learning (ML) to interpret hyperspectral and remote sensing data, bridging the "scale-divergence problem" by linking landscape observations to soil structural proxies. Furthermore, this paper highlights the capacity of AI to predict critical soil functions, such as hydraulic conductivity and aggregate stability, by modeling complex, non-linear biophysical interactions. Finally, we address current challenges regarding data scarcity and model interpretability (the "black box" problem), proposing a future research agenda focused on Hybrid Models (Physics-Informed AI) and Explainable AI (XAI) to ensure predictive accuracy is matched by mechanistic understanding. Ultimately, the integration of AI facilitates a fundamental shift in soil structure research from a descriptive discipline to a quantitative, predictive science capable of addressing pressing environmental challenges.

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# Machine learning-based prediction of plant-available nutrients in soils using multiple variable selection strategies

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**ABSTRACT**

Accurate quantification of soil nutrients is essential for precision agriculture, enabling optimized fertilizer application, yield improvement, and mitigating environmental impacts associated with nutrient overuse. Although machine learning based prediction models provide a rapid and cost-effective alternative to conventional laboratory analyses, their development is often limited by insufficient training datasets derived from small-scale laboratory experiments. To overcome this limitation, this study used an open soil database comprising approximately 16,000 samples. Three machine learning algorithms–random forest regression (RF), extreme gradient boost (XG-Boost), and support vector regression (SVR)–were implemented to predict soil macronutrients, including nitrogen (N), phosphorus (P), and potassium (K). Also, three correlation analyses–Pearson correlation analysis (LCA), mutual information evaluation (MI), and random forest-based importance ranking (IR)–were used to evaluate their impact on model performance. When the LUCAS database from European Soil Data Centre (ESDAC) was used, soil pH, electrical conductivity (EC), organic carbon (OC) were chosen as key variables. The OC was the most influential variable for predicting N, with a correlation coefficient of 0.89 in the LCA. In addition, all machine learning algorithms achieved high $R^2$ value and low root mean squared error (RMSE) for N prediction, especially with RF ($R^2$ = 0.90, RMSE = 0.81) and XG-Boost ($R^2$ = 0.90, RMSE = 0.81). For the prediction of available P ($P_2O_5$) and K, soil physicochemical characteristics database from Rural Development Administration National Institute of Agricultural Sciences (NASS) was used. The XG-Boost performed better than RF for both nutrients. For $P_2O_5$ prediction, RF model resulted in an $R^2$ of 0.18 and an RMSE of 361,13, while XG-Boost described $R^2$ of 0.30 and RMSE of 334.08. For K prediction, $R^2$ and RMSE showed 0.33 and 0.62 for RF, whereas XG-Boost achieved values of 0.41 and 0.58, respectively. The results indicate that further improvement in data processing and modeling is required. This study presents a systematic framework integrating open soil databases, machine learning modeling, and feature selection strategies to improve soil nutrient prediction. The approach can be further extended by integrating machine learning models with sensor-based measurements such as EC and near-infrared (NIR) to enable rapid, scalable, and cost-effective nutrient monitoring systems for data-driven precision agriculture and sustainable soil management.

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# Automatic segmentation of soil micromorphological images using a Convolutional Neural Network

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**ABSTRACT**

Commonly used software tools for the analysis of micromorphological images typically require well-defined and non-overlapping color characteristics for each object class. However, digital images of soil thin sections are characterized by pronounced non-stationarity. The overlap of color ranges among different micromorphological elements leads to errors in automatic classification, making expert involvement necessary and significantly slowing down the analysis workflow. To address the issue of non-stationarity and improve segmentation accuracy, convolutional neural networks with a U-Net architecture were developed. A first dedicated training dataset was compiled using Thixomet Pro and included thin sections of various soil types: chernozem, gleysol, solonetz, kastanozem, podzol and other.

A binary segmentation model was created to identify pores and aggregates. Segmentation quality was assessed using the Intersection over Union (IoU) metric, which reached 0.94 for PPL and 0.89 for XPL. These values indicate high segmentation accuracy, further supported by expert evaluation. The model reliably excludes air bubbles and regions of epoxy resin birefringence from the “aggregates” class, thereby improving the delineation of adjacent aggregates.

In addition, a model for multiclass segmentation was developed to differentiate the following micromorphological components: groundmass, pores, minerals, clay coatings, optically oriented clay, iron–manganese nodules, and black constituents including humus and plant residues. Multiclass segmentation presents particular challenges due to the overlap of color characteristics among micromorphological elements and the labor-intensity of producing a sufficiently representative training dataset. According to IoU metrics, the model confidently identifies groundmass and pores, whereas iron–manganese nodules, humus, and plant residues are segmented less accurately. Optically oriented clay and clay coatings are currently segmented poorly. These low metric values are explained by the pronounced class imbalance in the training dataset rather than limitations of the model itself.

Overall, the developed models demonstrate high performance in segmenting aggregates and pores, as well as solid results for the remaining micromorphological components.

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# AI Enabled Soil Moisture Monitoring for Real Time Drought Detection in the Western United States

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**ABSTRACT**

Drought severity is increasing across the western United States, placing growing pressure on ecosystems, agriculture, and water resources. Soil moisture is a master variable influencing plant stress, hydrologic responses, and drought development, yet it remains one of the least monitored and least understood components of the water cycle, despite being the largest reservoir of fresh water on Earth. This project integrates artificial intelligence (AI) with soil moisture sensors and drought indicators such as NDVI and thermal imagery to improve real-time detection and forecasting of drought conditions. Using the NSF Sage platform, which enables AI processing at the edge and supports integration of environmental data streams such as climate sensors, cameras, and other field-based measurements, we combine remotely sensed and ground-based observations to track soil water availability more accurately and at finer temporal scales. The goal is to demonstrate that AI trained models combining thermal data, vegetation indices, and soil moisture measurements can enhance the detection of early drought signals before they are visible in traditional monitoring products. This work will establish a scalable framework for real-time drought assessment across the Western Great Plains, providing timely, actionable information for stakeholders ranging from land managers to policymakers.

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# AI-Driven Data Mining of Scientific Literature: A Framework for Soil Research

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**ABSTRACT**

With the continuous output of research findings related to the soil environment, the volume of relevant scientific literature has grown exponentially. This presents formidable challenges for researchers to synthesize existing knowledge and identify research gaps through literature reanalysis. Traditional literature analysis methods, such as expert-led systematic reviews and meta-analyses, are constrained by manual processing limitations. These methods are typically limited to a few hundred publications, making them insufficient to meet the demand for in-depth mining of large-scale literature datasets. Accurately extracting in-depth scientific research data from extensive literature is a core prerequisite for advancing data-driven research in the soil environmental field. However, conventional manual data extraction methods suffer from inherent drawbacks, including high labor intensity, time-consuming procedures, significant subjective biases, and a high risk of human error. These limitations severely impede the efficiency of literature data utilization and the speed of research translation. In recent years, artificial intelligence (AI) technologies centered on machine learning have gradually demonstrated their capacity for large-scale literature analysis, providing a critical technical pathway to resolve the contradiction between the exponential growth of literature quantity and the inadequacy of effective comprehensive analysis capabilities. In particular, the rapid iteration of large language models (LLMs) has broken through the limitations of traditional semantic analysis, enabling researchers to accomplish complex, multi-dimensional scientific research tasks. This study proposes an LLM-based workflow for literature data mining, which can efficiently extract data from scientific literature with high precision ( $F1 > 0.95$ ). By adopting a human-in-the-loop expert feedback strategy, the workflow's feature extraction capability is effectively enhanced. This workflow exhibits excellent performance in literature data mining for soil environmental research and can provide robust support for the construction of domain-specific datasets for model training.

# 3D Two-stage Multi-modal Soil Pore Segmentation based on Flow Field

**ABSTRACT**

The morphological characteristics of soil pores are the core factors determining soil functional differentiation. There is significant heterogeneity in pore structure of different types of soil. However, current soil pore segmentation methods still face three core challenges when facing multi-type soil CT images, including soil type-specific interference, insufficient generalization of cross-type features, and unbalanced data in small samples. In order to solve the above problems, in this study, three typical soils, black soil, brown soil, and sandy loam, were selected as the research objects. Three-dimensional image data of soil pores were obtained by CT scanning, and a multimodal soil pore segmentation method based on flow field information was proposed. A one-dimensional flow model was constructed based on Darcy's law, and combined with the pore area heterogeneity distribution model and the dynamic pressure gradient between layers, the flow velocity distribution of soil pores was calculated. The reliability of flow field data was ensured by triple verification of physical rationality, numerical validity, and interlayer connectivity. The flow velocity information was used as the key modal feature and combined with the structural features of CT images to construct a multi-modal fusion segmentation framework (3DTM-UNet) to enhance the ability of the model to identify different types of soil pores. The results showed that the accuracy, precision, recall, and F1-score of 3DTM-UNet reached 99.8%, 95.5%, 94.5%, and 94.9%, respectively. Compared to the sub-optimal method ConvUNext, the F1-score was 6 percentage points higher. This study provides an efficient and reliable technical tool for the quantitative analysis of the pore structure of various types of soil, and the results can support research and practice in soil function optimization, quality assessment, and precision agriculture management.

**Keywords:** multi-modal, multi-types of soil, flow field, CT image, segmentation

# Multi-Class Segmentation of Soil Structure from CT Images based Deep Learning

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**ABSTRACT**

Computed tomography (CT) has been widely applied to quantify soil pore architecture and structural properties. However, most CT-based soil studies simplify soil structure into a binary system consisting of pores and mineral matrix, which limits the representation of soil heterogeneity and obscures the contribution of individual soil constituents. In particular, particulate organic matter (POM), rock fragments, and roots are rarely distinguished explicitly, despite their important roles in soil structural organization and biophysical processes.

In this study, a multi-class soil component segmentation framework is developed to identify and separate multiple soil constituents from CT images, including pores, POM, mineral soil matrix, rock fragments, and roots. High-resolution CT images were used to construct a multi-class representation of soil structure, moving beyond conventional pore segmentation. Deep learning-based image segmentation methods were employed to capture differences in grayscale intensity, textural features, and spatial context among soil components.

The proposed approach enables the explicit delineation of POM that is resolvable in CT images and allows its spatial distribution, volume fraction, and spatial associations with pores and roots to be quantitatively analyzed. Compared with traditional binary segmentation, the multi-component framework provides a more realistic and interpretable description of soil morphology and micromorphology. Preliminary results indicate that distinguishing POM and other solid components significantly improves the characterization of soil structural heterogeneity.

This work demonstrates the potential of deep learning-driven multi-class segmentation for advancing CT-based soil morphological analysis. By enabling explicit identification of CT-resolvable soil constituents, the proposed framework supports improved interpretation of soil structural organization and facilitates the integration of soil CT image repositories into quantitative soil process modeling.

# AI-Assisted Applications for Soil Science Education: Tools for Teaching and Learning

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**ABSTRACT**

Artificial intelligence (AI) is rapidly transforming education, creating new opportunities for improving the teaching and learning of soil sciences (Memari and Ruggles, 2025). Generative AI offers practical solutions to help students understand complex concepts and save time in analytical or repetitive tasks that often reduce instructional efficiency and student engagement (Holmes et al., 2019). Beyond simple interaction with existing AI assistants, a unique opportunity lies in the collaborative development of AI-assisted Applications (AI-apps), where users iteratively prompt AI systems through a natural language dialogue until the application meets their precise needs. This human-AI collaborative approach democratizes software development, allowing educators without programming experience to create specialized tools for specific teaching contexts and regional requirements. This work presents three examples of (Spanish/English) web-based AI-apps, developed primarily using Claude Sonnet 4.5 AI (Anthropic, 2025), ChatGPT PRO 5.2 (OpenAI, 2025) and Gemini PRO (Google DeepMind, 2025). 1) **EdafoConvert**: an application for unit conversions of basic physical, chemical, and biological variables used in soil science, including water potential (kPa, bar, atm), density, and nutrient concentrations. 2) **EdafoTexture**: an application for soil texture classification based on the USDA textural triangle. Users can input sand, silt, and clay percentages manually or interact directly with the triangle diagram to determine the textural class. It also includes batch processing capabilities for analyzing multiple soil samples simultaneously through Excel file uploads, and 3) **Soil-Water-Retention**: is an application for calculating soil water dynamics, including field capacity, permanent wilting point, and available water. Users can select from predefined soil textures (clay, silt, loam, sand) or input custom values, along with current moisture content, root depth and daily evapotranspiration rates for agricultural water management and irrigation planning. All these applications are freely accessible at https://sueloestudiarsuelos.com/apps. These AI-apps benefit both students and instructors, enhancing learning through interactive visualization of complex soil concepts, promoting autonomy and conceptual clarity (Kaur et al., 2023), automatizing repetitive tasks and enabling rapid creation of customized tools without programming experience, lowering technical barriers to educational innovation (Holmes et al., 2019).

**Keywords:** computer-assisted education, human-AI collaboration, active learning methodologies

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# SpecSINFERS: Soil Inference Systems in the AI era

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## ABSTRACT

A soil inference system is a software engine for the systematic prediction of soil properties from other soil properties readily available. Traditionally, tt consists of a collection of pedotransfer functions (PTFs) which are the knowledge rules that drive the inference process. In the AI era, advanced machine learning can also be integrated, combining powerful pattern extraction from large datasets and conventional soil knowledge. Given a user input (records with values of one or more soil properties; or measurements from a sensor), SpecSINFERS starts by predicting soil properties using all possible combinations of inputs and PTFs, assessing the uncertainty of each prediction. Then, a new round of predictions is started, using the input and predicted properties, automatically propagating the uncertainty at each step. This process continues until all the combinations of soil properties and PTFs are exhausted (Figure 1). During this process, SpecSINFERS also identifies when new predictions are outside the data domain in which the PTFs were generated, penalising the uncertainty in the presence of extrapolations. SpecSINFERS provides a way of organising knowledge in a carefully curated collection of PTFs that fulfil the requirements needed for uncertainty assessment. Additionally, it provides a systematic and consistent way of executing PTFs and applying uncertainty propagation. This tight coupling of model and uncertainty assessment ensures the correct use of PTFs. By using such a system, PTFs can be well documented and organised, not just in a journal paper, and thus promoting their use. It also opens the possibility of integration with other systems such as handheld devices (e.g. spectrometers) that can be used directly in the laboratory and the field to generate multiple predictions from a single reading.

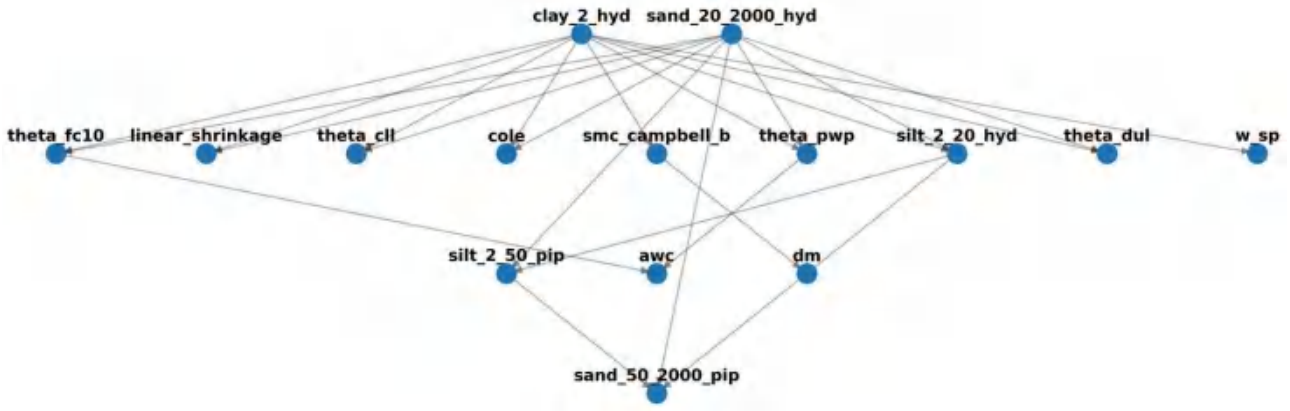



**Figure 1.** Example of the sequence of pedotransfer functions triggered by two soil properties (clay and sand content).

**Keywords:** symbolic regression, uncertainty propagation, soil modelling, spectroscopy

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# Segmentation of soil structural domains in thin-section images: a deep learning approach

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**ABSTRACT**

Soil structure plays a key role in regulating soil physical and biological functions. In soil micromorphology, its assessment from soil thin sections remains largely qualitative and strongly dependent on expert interpretation. This subjectivity limits reproducibility and hampers the systematic use of micromorphological information in quantitative soil analyses. Recent advances in deep learning offer new opportunities to support soil structure interpretation by learning spatial patterns directly from images; however, their applicability to soil micromorphology has not yet been systematically evaluated.

In this study, we investigate the feasibility of using deep learning–based semantic segmentation as a support tool for classifying soil structural units in thin section images. A dataset of binary thin section images, in which pores and solids were previously separated, was annotated according to major soil structural classes (massive, granular, crumb, blocky, and laminar). Several convolutional neural network architectures commonly used in semantic segmentation were trained and compared within a consistent experimental framework.

Model performance was evaluated on an independent test set using standard pixel-wise metrics, alongside a class-specific analysis. All tested architectures achieved high segmentation performance. Architectures explicitly designed to integrate multi-scale contextual information showed the most consistent performance across structurally heterogeneous classes.

This work provides an evaluation of the extent to which deep learning approaches can support soil structure interpretation from thin section images. The results suggest that deep learning–based segmentation has the potential to act as a decision support tool in soil micromorphological analysis, complementing expert interpretation and contributing to more reproducible and systematic assessments of soil structure.

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# CSDMS BMI model coupling for Soil Digital Twins

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**ABSTRACT**

The work presents a Soil Digital Twin (SDT) integration framework coupling physically-based models across spatial scales from pore microstructure to landscape level for predictive simulation of soil-water-plant interactions. The integration follows CSDMS Basic Model Interface (BMI) methodology [1], enabling interactive runtime variable exchange where outputs from one model directly feed as inputs to another.

We developed a unified standard for model description containing model identification, physical description, BMI metadata including variables with CSDMS Standard Names, grid, time parameters, and coupling protocols allowing for compatibility verification and unit conversion during model linkage.

The SDT couples four model types: Erosion models include WaTEM/SEDEM [2] implemented in Python, and LISEM [3] with C++ core for event-scale Richards equation infiltration and kinematic wave routing. Crop models feature AquaCrop [4] with Fortran implementation for crop productivity and canopy dynamics, alongside DSSAT [5] for phenological modeling. ParFlow-CLM [6] couples subsurface flow with land surface processes. PNFlow extracts pore networks from X-ray CT, calculating van Genuchten parameters and permeability curves.

Models register as Python packages with pymt.plugins entry points exposing initialize(), update(), and finalize() methods. Runtime data exchange occurs through get_value() and set_value() methods. Grid information retrieves via get_grid_*() methods. Babelizer generates Python wrappers for non-Python components (C++, Fortran) enabling coupling across heterogeneous codebases.

Extensive validation of the system was caried out at Dokuchaev Soil Science Institute experimental site (Tver Oblast, Russia)

**Acknowledgments**

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# Precise Source Apportionment and Spatial Distribution Prediction of Soils Heavy Metals Pollution in the Largest Magacity in China Based on Multi-source Data and Machine Learning

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## ABSTRACT

Accurate identification of heavy metal pollution sources and their spatial distribution is critical for soil pollution control. However, the complex spatial heterogeneity of these pollutants poses significant technical challenges for large-scale source apportionment and high-risk area identification. Taking one of the largest megacities in China, such as Shanghai, this study integrates multi-source environmental data to systematically compare the predictive performance of eight machine learning models (ML), including Random Forest, Extreme Gradient Boosting, and Extra Trees, for five heavy metal contents in farmland soil: arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb). Results show that the Extremely Randomized Trees (ET) model achieved optimal predictive performance, with test-set $R^2$ values ranging from 0.57 to 0.67, demonstrating both strong predictive accuracy and robustness. Spatial predictions based on the ET model indicate significant enrichment of Cd and Hg in traditional industrial zones such as Baoshan and Jiading. Meanwhile, elevated concentrations of As and Pb are primarily distributed in Chongming, Pudong, and along riverine industrial-transportation corridors. In contrast, Cr shows a relatively uniform spatial distribution, consistent with natural background controls. Further analysis of driving factors reveals that the distributions of Pb and As are primarily influenced by climatic and hydrological processes, Hg accumulation is dominated by soil physicochemical properties, and Cd exhibits a characteristic “natural-anthropogenic” composite driving pattern, with significant contributions from GDP and population density. This study confirms the effectiveness of ML in integrating multi-source data to elucidate the spatial variability and driving mechanisms of soil heavy metals, providing methodological support for precise source identification, risk zoning, and targeted pollution control in megacities.

# Improving Conservation Tillage Systems: Soil EC and pH Management through Rotation, Nutrition and Microbial Interventions

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**ABSTRACT**

This presentation addresses core challenges in conservation tillage, emphasizing the critical impact of soil physicochemical indicators—particularly EC and pH values—on crop growth and farmland quality. Analysis of a wheat cultivation case study in Shilin County identifies excessively low EC values as a key constraint leading to crop growth inhibition and even plant death, highlighting widespread soil fertility deficiency as a prominent issue in cultivated land quality.

In response, a systematic improvement framework is proposed and practiced in Shilin County: optimizing crop structures through rotations such as tobacco–buckwheat–potato–corn, combined with integrated nutrient management emphasizing organic and micronutrient fertilizers, continuous application of microbial inoculants, and straw return to the field. These measures aim to enhance soil organic matter, stabilize pH, rationally adjust EC levels, and effectively control potential contaminants.

The ultimate objective is to establish a location-adapted, crop-structured, and scalable conservation tillage protocol that promotes sustainable soil quality improvement, balancing economic, ecological, and social benefits in agricultural production.

# Jingmai Mountain's Ancient Tea Forests: A Model of Forest- Tea Symbiosis, Biodiversity, and Cultural Heritage

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**ABSTRACT**

The ancient tea forests of Jingmai Mountain in Yunnan are an outstanding example of the ecological wisdom behind "forest-tea symbiosis." This system mimics the structure of a natural forest: a canopy formed by tall trees such as camphor at the upper layer, tea trees in the middle layer, and dense herbaceous plants at the lower layer. The forest provides shade and maintains humidity for the tea trees, while fallen leaves and branches decompose into natural green manure, nourishing the soil. This multi-layered, low-intervention model not only shapes the distinctive aroma profile of Pu'er tea but also creates an integrated habitat where birds, insects, orchids, ferns, and small mammals thrive, achieving deep synergy between agricultural production and biodiversity conservation.

The rich biodiversity also enhances both the flavor and value of the tea. For instance, the Blang people utilize microorganisms from the forest floor to ferment tea leaves, producing their unique Blang sour tea. The ethnic culture, passed down through generations, further injects enduring vitality into the sustained protection and rational use of this system.

# Effects of Dry Direct-Seeded Rice and No-Till Soybean Cropping After Rice on Soil Health and Nutrient Utilization in the Puer Region

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**ABSTRACT**

To address water resource constraints and enhance the multiple cropping index in mountainous regions, Pu'er City in Yunnan, China, has promoted two innovative planting models: Dry-seeded Rainfed Rice and Post-rice No-till Soybean.

Results indicate that compared to traditional paddy fields, the Dry-seeded Rainfed Rice model reduces irrigation water usage by 60%, significantly improves soil physical structure, and enhances soil aeration and infiltration capacity.

Planting no-till soybeans after the rice harvest fully utilizes the soil ecological environment and residual nutrients of the preceding crop. This model reduces the system's reliance on external nitrogen fertilizers through the biological nitrogen fixation of the leguminous crop. The study reveals that the soybean rotation phase increased Soil Organic Carbon (SOC) and Total Nitrogen (TN) stocks to 59.04 Mg/ha and 4.03 Mg/ha, respectively, significantly outperforming monoculture cereal systems. Additionally, this conservation tillage approach minimizes soil disturbance, helping to reduce nitrogen and phosphorus losses caused by surface runoff by approximately 25%.

The integrated application of these two models serves as an effective strategy to enhance soil productivity, boost carbon sequestration, and promote sustainable agricultural development in mountainous drylands by optimizing the soil water-air environment and stimulating soil biological activity.

# A Climate Change Perspective on Yunnan's Diverse Response Strategies

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**ABSTRACT**

In response to climate change, Yunnan is tapping into its rich natural environment and agro-biodiversity. Given the province's diverse geography, climate conditions, and ecosystems, its core approach is "using diversity to confront uncertainty." This includes deploying varied crop varieties and farming systems across different elevations; promoting multi-layered mountainous agriculture to improve resource efficiency; preserving and applying traditional ecological knowledge and adaptive practices from local ethnic groups; and developing climate-resilient specialty crops and adapted varieties. Together, these measures help farmers manage climate risks while strengthening the overall resilience and adaptive capacity of agricultural systems in the region.

To further explore these strategies, we are convening a Panel Discussion focused on Yunnan's Diverse Pathways for Climate Adaptation. We invited guests from across Yunnan to join us and share their experiences and insights.

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# Building Climate-Resilient Agriculture through Multi-Stakeholder Engagement: The PEAC Model

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**ABSTRACT**

Established in 2002, Pesticide Eco-Alternatives Center (PEAC) is a provincial-level 4A social organization dedicated to collecting, systematizing, and promoting environment-friendly and climate-friendly agricultural technologies. It focuses on exploring integrated pathways to reduce agricultural pollution, lower carbon emissions, and enhance climate adaptation, thereby advancing sustainable agricultural development. Currently, PEAC's work centers on three key areas: climate-smart rice farming, soil conservation, and agro-biodiversity.

In its efforts to address climate change and promote conservation agriculture, PEAC has developed a systematic working strategy grounded in "science-based evidence, community-driven practice, and network-enabled collaboration." This approach is implemented through three interconnected levels:

First, PEAC engages deeply with the local communities through participatory innovation. By conducting on-farm demonstrations, organizing farmer training, and facilitating co-creation of adapted techniques in rural Yunnan, it ensures that farmers can use and validate the technologies. Their feedback is continuously integrated to refine technical manuals and enhance the practicality and effectiveness of the approaches.

Second, PEAC actively builds cross-sector collaboration networks to foster multi-stakeholder engagement in sustainable agriculture. It brings together diverse actors such as local agricultural extension stations, Yunnan Normal University, provincial academies of agricultural sciences, NGOs, village committees, family farms, farmer associations, and local farmers. By integrating policy, academic, and social resources, PEAC strengthens collective action and amplifies impact.

Finally, PEAC works to develop scalable and replicable regional solutions. Through participatory testing, it identifies climate-resilient crop varieties and promotes practices that save water, enhance soil moisture retention, and reduce chemical fertilizer and pesticide use. These field-tested experiences are systematized into standardized technical materials and training modules. Through hands-on demonstration, knowledge exchange, and policy advocacy, PEAC helps transition climate-smart agricultural practices from local piloting to broader industry recognition and policy support.

This "research–practice–network–advocacy" model highlights the crucial role of multi-stakeholder engagement in advancing climate-resilient agriculture. It provides actionable and sustainable guidance for locally adapted agricultural transformation toward greener development.

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# Combined Application of Organic and Inorganic Fertilizers Increases Maize Yield in Upland Acidic Red Soils by Enhancing soil chemical properties and aggregate characteristics

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**ABSTRACT**

Organic-inorganic fertilization is a key practice for enhancing soil fertility and crop yield, yet its response mechanisms under different fertilizer combinations in low-latitude plateau upland red soils remain poorly understood. Based on a 45-year long-term field experiment (1978–2022) in the red soil area of Qujing, Yunnan, this study evaluated the effects of various fertilizer regimes—including chemical fertilizers (N, NP, NPK) and their combinations with organic manure (NM, NPM, NPKM)—on maize yield, soil nutrients (pH, soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), available phosphorus (AP)), and aggregate structure (the proportion of aggregates > 0.25 mm ($R_{0.25}$), water-stable aggregates($WSAC_{0.25}$), mean weight diameter (MWD), geometric mean diameter (GMD), percentage of aggregate disruption (PAD), fractal dimension (D)). Results showed that compared with the no-fertilizer control (CK), organic-inorganic fertilization significantly increased maize yield by 178.83%–188.19% and raised economic returns by 116.32%–122.10%. It also alleviated soil acidification, maintaining topsoil and subsoil pH above 6.0, while significantly increasing SOC, TN, and AN by 22.08%–31.69%, 11.18%–26.32%, and 20.00%–31.82%, respectively. In terms of soil structure, organic-inorganic fertilization enhanced macroaggregate content ($R_{0.25}$) and stability (MWD, GMD) in the 0–15 cm layer by 13.40%–41.18%, 7.37%–44.21%, and 19.44%–66.67%, respectively, while significantly reducing PAD by 25.00%–26.92%. These effects were more pronounced in the topsoil than in the 15–30 cm layer. Correlation analysis indicated that maize yield was closely associated with both soil chemical properties and aggregate structure, with chemical properties exerting a stronger influence. Random forest modeling identified TN and AN as the primary yield contributors (both 12.5%), while $R_{0.25}$ was the most influential aggregate parameter (7.9%). In conclusion, long-term organic-inorganic fertilization promotes maize yield by synergistically improving soil nutrient availability and structural stability. The NPM treatment performed best in terms of yield, economic benefit, soil quality enhancement, and nutrient retention, offering a sustainable fertilization strategy for upland red soil agriculture.

**Keywords:** organic amendment; inorganic fertilizer; acidic upland soil; yield enhancement; aggregate stability; soil fertility.

**Acknowledgments**

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# An Ecological Farming Model for Climate Adaptation: Synergizing Soil Health and Community Resilience in Yunnan's Rice Paddies

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**ABSTRACT**

Chonglie Xu operates an experiential ecological farm in Eryuan, Dali, and manages a Community Supported Agriculture (CSA) network in Dayun. In rice cultivation, he actively practices ecological farming principles by integrating multiple climate-friendly agronomic measures, systematically developing a cultivation model that enhances both environmental and production benefits. Through field management techniques such as ridging, trenching, and furrow irrigation, combined with the rice-fish co-culture system, he has significantly reduced the reliance on chemical fertilizers and pesticides, achieving truly ecological cultivation. Water-saving practices like furrow irrigation not only lower water consumption but also effectively suppress methane emissions from paddy fields.

Furthermore, this model highlights climate-friendly measures such as variety selection, organic fertilizer application, and soil conservation, which continuously increase soil organic carbon storage and enhance the carbon sequestration capacity of farmland. These practices improve the agricultural system’s adaptability to climate change, promote the virtuous cycle of the field ecosystem and soil fertility, and ultimately boost comprehensive ecological benefits while strengthening the climate resilience and sustainability of community livelihoods.

# Functional characterization of key transporters regulating iron distribution in rice node

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**ABSTRACT**

Iron (Fe) distribution in rice is a critical determinant of both plant productivity and grain nutritional quality, with nodes serving as central hubs for inter-vascular nutrient transfer. Here, we integrate the functional characterization of three key node transporters—OsVIT2, OsVMT, and OsIET1—that orchestrate Fe homeostasis through distinct subcellular mechanisms. OsVIT2 (vacuolar iron transporter) and OsVMT (vacuolar mugineic acid transporter) are tonoplast-localized proteins that sequester $Fe^{2+}$ and the phytosiderophore 2'-deoxymugineic acid (DMA) into vacuoles of parenchyma cell bridges and aleurone layers, respectively. Knockout of either gene disrupts vacuolar sequestration, resulting in enhanced Fe/Zn accumulation in polished grains (1.4–2.1-fold increase) without yield penalty, demonstrating their potential as sustainable biofortification targets. In contrast, OsIET1 (iron efflux transporter 1), a plasma membrane-localized VTL-clade protein, functions as a proton-coupled $Fe^{2+}$ efflux transporter specifically expressed in the xylem region of diffuse vascular bundles. Its disruption impairs Fe reloading into the xylem, causing excessive Fe deposition in nodes, chlorosis in young leaves, and a 38–48% yield reduction under Fe-limiting conditions. While OsVIT2 and OsVMT act as molecular "gates" that limit Fe mobility through sequestration, OsIET1 acts as an essential "pump" that drives preferential Fe allocation to developing tissues. Collectively, these transporters reveal a coordinated system where vacuolar storage capacity and plasma membrane efflux activity balance Fe partitioning between vegetative tissues and grains, providing complementary genetic strategies for either enhancing grain micronutrient content or ensuring optimal plant growth.

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# Effects of Different Acidic Intensities on the Yield of Peanut Genotypes

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## ABSTRACT

Over the past three decades, soil acidification in China's southern red and yellow soil regions has intensified, posing severe threats to agricultural sustainability and national food security[1]. Based on the 2015 National Soil Survey, acidic (pH ≤ 6.5) and strongly acidic (pH ≤ 5.5) soils account for 32.4% and 4.7% of China's terrestrial area, respectively [2], inducing soil fertility degradation[3, 4], increased heavy metal bioavailability[5], reduced microbial community diversity[6], and over 20% crop yield loss in strongly acid-stressed areas[1]. As a major oil crops supporting national oil supply security (contributing 27.9% to China's oil crop yield growth from 2007-2022[7]), peanuts face persistent yield limitation in these acidic soils: 2007-2016 monitoring shows southern peanut yields are only 70.6% of the national average[8]. Previous studies identify strong acid stress and low soil fertility characteristics as key yield-limiting factors [2, 9], with field data confirming significantly reduced peanut biomass and fresh pod weight at pH 4.70 (strongly acidic) compared with pH 5.58 (suitable acidity)[10]. To address this bottleneck, this study aimed to: (1) clarify how soil acid intensity regulates peanut yield-related traits across genotypes; (2) screen acid-tolerant varieties suitable for southern acidic soils; and (3) explore nutrient dynamics underlying genotype-specific acid stress responses.

To achieve these objectives, a field plot experiment was conducted with three soil pH gradients (pH 4.44, pH 4.70, and p H 5.23; 4 replicates each) and four peanut varieties (S23_0202, S23_0310, ZYH100, and Pukehua 16). were selected for p lanting. Key yield traits (pod dry weight, 100-kernel weight) and nutrient dynamics (bulk/rhizosphere soil available P/K, pl ant N/P/K contents) were measured to evaluate genotypic differences in acid stress responses.

Regarding yield trait regulation, pod dry weight correlated positively with soil pH for ZYH100, S23_0202, and Pukehua 1 6 (significant gradient differences), while S23_0310 maintained stable pod dry weight—confirming soil acid intensity indire ctly regulates yield via pod number and kernel weight, with substantial genetic variation in responses. This finding further raised a critical follow-up question: Do peanuts adopt resource allocation trade-offs (prioritizing pod formation vs. kernel development) under acid stress?

For acid tolerance screening, 100-kernel weight (a key commercial value indicator) identified pH 5.23 as the optimal soil pH. At pH 4.70, S23_0310 (90%), S23_0202 (86%), and Pukehua 16 (89%) retained high relative 100-kernel weights, whi le ZYH100 dropped to 62% (severe kernel inhibition). At pH 4.44, tolerance rankings were: Pukehua 16 (88%) > S23_02 02 (77%) > S23_0310 (65%) > ZYH100 (52%).

For nutrient dynamics, bulk soil available P/K was medium-to-high (sufficient for growth), and all varieties had higher rhi zosphere available K than bulk soil (potentially drought stress adaptation[11]). No genotypic differences were observed in ro ot N/P/K or aboveground P/K, but S23_0310 had significantly lower aboveground N—suggesting a potential link to its uni que yield stability under acid stress (needing further investigation).

These findings carry significant practical and scientific implications: we provide targeted acid-tolerant peanut varieties for g raded acidic soils (Pukehua 16: strongly acidic; S23_0310/S23_0202: moderately strongly acidic; ZYH100: weakly acidic), establish a basis for exploring nutrient allocation and nitrogen metabolism mechanisms of acid tolerance, and thus facilitate high-yield, high-quality peanut production in southern China's acidic soil regions.

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# Differential Allocation of Cadmium and Zinc in Soil-crop Systems

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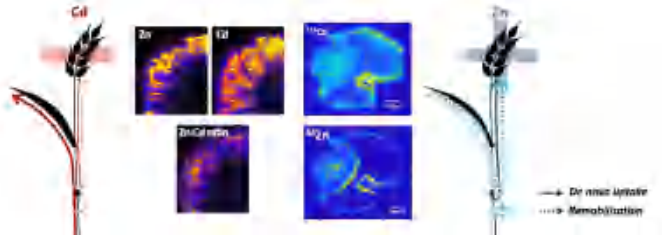
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**ABSTRACT**

Managing the accumulation of toxic cadmium (Cd) and the biofortification of essential zinc (Zn) in cereals is a critical challenge for global food security and human health. Due to their similar chemical properties, these elements often share transport pathways from soil to grain, making it difficult to differentially regulate their accumulation. This presentation synthesizes findings from Sino-French collaborative research using cutting-edge technologies, including stable isotope tracing, synchrotron X-ray fluorescence, and laser ablation ICP-MS, to reveal the eco-physiological mechanisms governing the distribution of these metals in crops.

Research into the flux of Cd and Zn in soil-plant-grain systems shows that soil management is the first line of defense: organic amendments contribute essential Zn by increasing its available pool while effectively immobilizing Cd, thereby reducing its availability. Within the plant, remobilization from pre-anthesis vegetative pools contributes significantly to grain metal loading, typically accounting for 35–60% of total grain accumulation. However, Zn is remobilized much more efficiently than Cd, which is often trapped by high-transpiring vegetative organs. These organs, such as flag leaves and bracts, act as irreversible sinks for Cd, limiting its allocation to the edible grain. In contrast, these same tissues serve as primary sources for Zn remobilization during senescence.

Within the grain of wheat, the crease and periphery (maternal tissues) function as critical regulatory point. High-resolution imaging identifies the crease as the main barrier to Cd and Zn loading into the edible endosperm, while isotope tracing reveals that this barrier is more restrictive for Cd than for Zn. During grain development, while Cd remobilization remains restricted within the maternal tissues, Zn is significantly remobilized from the crease and periphery to the endosperm. These findings demonstrate that agronomic strategies targeting soil organic matter, tissue senescence, and post-harvest processing can be applied to selectively reduce Cd while maintaining or increasing Zn levels in cereal-based foods, thereby improving food safety while supporting micronutrient biofortification.



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# Advancing the rhizosphere metabolic circular economy framework

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**ABSTRACT**

The rhizosphere metabolic circular economy (RMCE), first explicitly defined by Korenblum et al. (2022), operates as a coevolutionary system underpinned by three interconnected core mechanisms: reciprocal metabolic exchange, iterative reuse of resources, and adaptive remodeling of plant-microbe interactions. At its foundation is the unidirectional yet reciprocally beneficial flow of C from plants to microbes, a complex mixture of primary metabolites (sugars, organic acids, amino acids) and specialized secondary metabolites (flavonoids, coumarins, triterpenes), which act as both nutritional substrates and signaling molecules to select and nourish specific microbial taxa. Since its formal definition in 2022, accumulating research—spanning multi-omics, synthetic microbiology, field ecology, and molecular genetics—has expanded the RMCE framework beyond the initial "binary plant-microbe interaction" model, integrating spatial, functional, regulatory, and ecological dimensions that refine its complexity and practical relevance. A primary update lies in the recognition of spatial heterogeneity as a defining feature of RMCE, replacing the view of the rhizosphere as a homogeneous habitat. A second critical update is the expansion of RMCE's circular carriers to include the "live-dead microbe continuum"; the microbial necromass—accounting for 30–50% of SOM—functions as a slow-cycling C sink. Third, the framework now incorporates quantitative functional metrics that move beyond qualitative "no-waste" descriptions. Fourth, RMCE is now recognized as integrated with regulatory networks and complex multi-trophic interactions (e.g., viral-bacterial-fungal-plant cross-talk) that balance nutrient acquisition and defense. Fifth, RMCE is now viewed as an environmentally adaptive system capable of restructuring under various stress. Together, these updates redefine RMCE as a spatially structured, dynamically regulated, and ecologically complex system, providing a more comprehensive foundation for its optimization in sustainable agriculture.

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# bHLH IVb Subfamily Precisely Regulate Iron Homeostasis in Rice

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**ABSTRACT**

Iron (Fe) is an essential element for plants, yet becomes toxic when in excess. Plant Fe homeostasis is primarily controlled by many basic Helix-Loop-Helix (bHLH) transcription factors (bHLH TFs). Our previous studies identified three IVb bHLH TFs—OsbHLH061, OsbHLH062, and OsbHLH063—as important negative regulators of Fe homeostasis, although coordinated function of subgroup IVb bHLH TFs remained unclear. Here, we show that rice subgroup IVb proteins play critical, redundant, yet functionally divergent roles in responding to changes in Fe availability. Higher-order mutants of *OsbHLH061/062/063* exhibited hypersensitivity to Fe deficiency and a marked overaccumulation of Fe under sufficient-Fe conditions. We demonstrate that OsbHLH061, which is induced by Fe and exhibits the highest affinity TOPLESS/TOPLESS-RELATED co-repressors (TPL/TPRs), plays a predominant role in repressing Fe accumulation and related gene expression under sufficient-Fe conditions. In contrast, OsbHLH063 is largely induced by Fe deficiency and plays more critical roles in Fe deficiency adaptation; notably, OsbHLH063 is essential for preventing photobleaching under low-Fe conditions. In addition, OsbHLH064, another IVb member, has minimal impact on Fe homeostasis. Our work elucidates a sophisticated regulatory paradigm in which orchestrated expression, genetic redundancy, and functional divergence within a transcription factor subgroup enable tight tuning of Fe homeostasis in rice.

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# Unveiling the Microbial Terroir: Soil-Driven Microbiota Assembly Modulates Grapevine Potassium Uptake and Fruit Volatile Accumulation

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## ABSTRACT

Agricultural products with unique flavor compounds were attributed to their place of origin, which is known as 'terroir'. In grapevine, the contribution of soil terroir (physicochemical properties) to wine grape quality has been well documented, yet the mechanisms linking soil nutrients, plant-microbe interactions, and fruit metabolism remain elusive. This study investigated the effect of soil-driven microbial terroir to grape flavor quality.

In this study, the multi-omic analysis were conducted for the soil property, microbiome (soil, rhizosphere and fruit surface), transcriptome (root, berry) and metabolome for three grapevine cultivars (Cabernet Sauvignon, Merlot, and Chardonnay) of six sites in Ningxia region (China). Results showed a strong positive correlation between soil available potassium (K) levels and grape berry pH. Transcriptomic profiling of grapevines growing in high-K soils indicated an upregulation of $K^+$ transporter genes (*VvKUP8* and *VvKUP10*). Co-occurrence network analysis further highlighted that these high-K conditions were associated with distinct shifts in the rhizosphere microbiome structure, specifically an enrichment of bacterial genera such as Niastella, Ensifer, and Sphingomonas. These findings suggest a potential link where soil K availability shapes specific microbial communities that co-exist with high-pH fruit phenotypes.

Beyond the rhizosphere, we further explored how these edaphic-driven microbial patterns extend to the carposphere (fruit surface) to shape fruit flavor (Liu et al., 2025). Results showed the assembly of the grape carposphere microbiome was primarily driven by environmental conditions rather than grape genotype. Further, operational taxonomic units (OTUs) within the genus Sphingomonas were strongly correlated with the production of C6 aldehyde volatiles, also known as green leaf volatiles (GLVs), which contribute to the fresh, green taste of the grapes. A key core gene set enriched in lipid metabolism was found to regulate both bacterial colonization and the activation of C6 aldehyde volatile synthesis, and the *VvLOX* gene playing a crucial role in this process. The microbe-metabolite relationship was further confirmed through inoculation of Sphingomonas sp. on the berry skin of two grape cultivars, resulting in increased GLV production.

Collectively, our findings establish a microbial link between soil properties and fruit quality attributes. We propose that soil factors not only directly supply nutrients but also act as selective filters for functional microbiomes that regulate both fruit acidity (via K uptake) and regional aromatic typicality (via VOC metabolism). This study offers a theoretical basis for manipulating the "soil-microbiome-fruit" continuum to improve grape quality in distinct terroirs.

**Acknowledgments**

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# Engineering biological interaction networks for soil health: principles, applications, and prospects

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**ABSTRACT**

Soil pollution poses a profound threat to ecosystem and human health. Moving beyond the traditional, often ineffective single-species remediation paradigm, this review proposes and elaborates a novel framework: biological interaction networks as the core engine driving efficient and sustainable soil decontamination. We systematically dissect the architecture and dynamics of key interactions, including plant-plant, plant-microbe, and microbe-microbe interactions, within remediation contexts, elucidating how mechanisms like mutualism, competition, and cross-kingdom signaling govern the fate of heavy metals, organic pollutants, and complex mixtures. Crucially, we explore how these natural networks can be actively engineered through strategies such as targeted bioaugmentation, precision biostimulation, and rational plant community assembly to enhance remediation outcomes. Furthermore, we highlight how cutting-edge multi-omics, synthetic ecology, and computational modeling are transitioning the field from descriptive ecology to predictive network design, enabling the decoding of the soil black box and the rational construction of tailored, resilient remediation consortia. Finally, we discuss the ecological challenges of introducing designed networks and outline a future road map toward precision restoration ecology, where theory-guided interaction network management enables effective, stable, and ecologically sound soil clean-up. This network-centric paradigm represents a fundamental shift from experience-based trial-and-error to a principled design approach for restoring soil health.

**Keywords:** Heavy metals; microbial community collaboration, or¬¬¬¬ganic pollutants; plant-microbe symbiosis; rhizosphere microecology; soil bioremediation; synthetic microbial communities (SynComs)

# A leaf sheath-localized Mn-nicotianamine complex transporter OsYSLc coordinates manganese distribution and detoxification in rice

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## ABSTRACT

Manganese (Mn) is an essential micronutrient but becomes toxic when accumulated in excess. The leaf sheath is proposed to function as a buffering compartment that temporarily stores Mn, ensuring a steady supply to developing tissues while preventing excessive accumulation in young organs. However, how rice coordinates Mn distribution and detoxification between these tissues remains poorly understood. Here, we identify OsYSLc, a member of the Yellow Stripe-Like (YSL) transporter family, as a plasma membrane-localized Mn-nicotianamine (Mn-NA) transporter with dual functions in Mn distribution and detoxification in the rice leaf sheath. GUS staining showed that OsYSLc is predominantly expressed in the leaf sheath, specifically in the phloem and cortical parenchyma cells. Heterologous expression and in planta transport assays demonstrated that OsYSLc mediates Mn transport in complex with nicotianamine. Loss-of-function *osyslc* mutants accumulated excessive Mn and Zn specifically in the leaf sheath of old leaves, including both the apoplastic and symplastic fractions, whereas metal levels in the leaf blade and developing tissues were slightly reduced.This indicates that disruption of OsYSLc traps Mn in the leaf sheath, leading to functionally reduced Mn availability in growing organs despite high total Mn levels in old tissues.Transcriptome analysis further revealed that several metal uptake genes, including *OsNRAMP5*, were significantly upregulated in the roots of *osyslc* mutants, likely as a systemic compensatory response to the perceived Mn deficiency in developing tissues. This shoot-to-root feedback enhances metal uptake but further aggravates Mn overaccumulation in the leaf sheath due to impaired internal redistribution. As a consequence of impaired Mn redistribution, *osyslc* mutants exhibited strong sensitivity to excess Mn, indicating that OsYSLc is required not only for Mn allocation to growing tissues but also for preventing toxic Mn accumulation through controlled internal detoxification. Field experiments showed similar ion distribution patterns, confirming the physiological relevance under agronomic conditions. In addition, *osyslc* mutants displayed increased concentrations of Fe, Mn, Cu, and Zn in grains. Thus, we propose that OsYSLc functions as a regulated “reservoir-and-valve” system in the leaf sheath, with cortical parenchyma cells serving as a Mn storage reservoir and the phloem acting as a conduit to developing leaves; OsYSLc mediates Mn release to young tissues as needed while retaining excess Mn in the reservoir to prevent toxicity. Furthermore, the increased micronutrient accumulation in *osysl1c* grains suggest that OsYSLc may be a promising target for mineral biofortification in rice.

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# Variation in Nitrogen Utilization Efficiency and Yield of Different Peanut Varieties

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## ABSTRACT

Peanut (*Arachis hypogaea L.*) is a globally important economic crop and oil crop, with an oil content ranging from 40% to 60% [1]. In 2024, China's peanut planting area will reach 4.837 million hectares, with a total output of 18.983 million tons, ranking second worldwide in planting area and first in total output, accounting for 16.7% and 37.7% of the global total respectively [2]. Fertilizers are critical for ensuring stable and high crop yields; however, long-standing issues in China's agricultural production—such as excessive fertilizer application, low utilization efficiency, neglect of soil nutrient resources, unregulated environmental nutrient inputs, underutilized crop yield potential, and ineffective control of nutrient loss—have not only increased production costs but also triggered environmental problems [3,4]. While strategies to improve fertilizer use efficiency exist (e.g., soil structure improvement, pH adjustment, scientific fertilization, and optimized fertilization techniques), these methods often require high technical expertise and incur substantial costs. Thus, leveraging the yield potential of existing peanut varieties, rather than relying on large-scale water and fertilizer inputs, is essential to simultaneously achieve high yields and efficient nutrient utilization.

Current research on fertilizer use efficiency globally has primarily focused on major food crops such as rice [5], wheat [6], and corn [7], with relatively limited attention to oil crops like peanuts and rapeseed. Additionally, much of the existing research on peanuts relies on laboratory pot experiments, which poorly simulate natural field conditions and lack practical applicability, leading to a gap between research findings and real-world agricultural production. Furthermore, research on peanut nutrient utilization efficiency lags behind, particularly regarding differences in nutrient use efficiency among diverse germplasm resources and the underlying mechanisms. To address these gaps, this study integrated field and pot experiments, employed a multi-index comprehensive evaluation system, and aimed to screen peanut germplasm resources with efficient nutrient utilization, and clarify the mechanisms governing this efficiency.

In this study, six fertilization treatments were established, each with four replicates: no-fertilizer control (CK), nitrogen omission (PK), phosphorus omission (NK), potassium omission (NP), full nitrogen-phosphorus-potassium (NPK), and NPK + organic fertilizer. A total of 18 representative peanut varieties from different regions were initially evaluated. Based on measurements of single-plant yield under different nutrient treatments, six varieties (YH76, S23-0303, ZYH100, S23-0202, Pukehua 16, S23-0044) were selected as key research objects to explore the relationship between nutrient utilization efficiency and yield.

Significant differences in nitrogen utilization efficiency (NUE) were observed among the six peanut varieties. Specifically, the NUE of S23-0044 (≈34%) and Pukehua 16 (≈33%) was significantly higher than that of YH76 (≈21%) and S23-0303 (≈22%). Nutrient supply exerted a significant positive effect on yield: all varieties achieved the highest yield under the NPK treatment, and yields in nitrogen-containing treatments (NP, NK) were significantly higher than those in the nitrogen-deficient treatment (PK), confirming that balanced nutrition promotes peanut nutrient absorption. Correlation analysis revealed a weak positive correlation between NUE and single-plant yield under NPK treatment ($r = 0.444$), which was not statistically significant ($P > 0.05$). This finding challenges the conventional assumption that "high NUE necessarily corresponds to high yield": for example, S23-0044 exhibited high NUE (34%) but a relatively low single-plant yield (61 g), while ZYH100 achieved both high NUE (29%) and high single-plant yield (87 g). These results demonstrate that peanut nutrient efficiency and yield do not follow a simple linear relationship, providing critical foundational data for future research on variety-fertilization interactions.

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# Influence of colloidal pools on soil phosphorus (P) bioavailability under organic fertilizer applications

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## ABSTRACT

Phosphorus (P) is essential for agricultural production but remains one of the least efficiently used nutrients, leading to both resource depletion and environmental losses. In France, organic fertilizers have been increasingly applied since the 1950s to reduce reliance on mineral P inputs. While long-term organic fertilization generally increases total soil P (TP) stocks, its effects on plant-available P (AP) are highly variable and poorly understood. In many cases, increases in TP do not consistently increase AP, highlighting the role of soil processes in influencing P availability. Soil AP includes not only by dissolved phosphate in soil solution but also by diffusive phosphate replenished from solid-phase pools. A substantial fraction of soil P is stored in colloidal and particulate forms, which act as dynamic buffers affecting P availability. Among these pools, P associated with water- dispersible colloids (WDC-P, <450 nm) represents a highly mobile and potentially bioavailable fraction. Despite its recognized role in off-site P transfer and environmental pollution, the contribution of WDC-P to sustaining soil P availability under different organic fertilization regimes remains largely unexplored. This contribution proposes a process-based perspective in which WDC-P acts as a dynamic phosphate reservoir whose contribution to soil AP depends on colloid behavior, fertilization type, and time since application. Focusing on long-term organic fertilization, the presentation will discuss (i) how different organic fertilizers affect WDC and WDC-P dynamics, (ii) how WDC-P may contribute to both chemically defined and diffusion-controlled AP pools, and (iii) how temporal changes in colloidal behavior influence soil P availability. By linking soil colloidal processes to P availability, this work highlights the potential of organic fertilization strategies to sustain soil fertility through controlled-release mechanisms rather than repeated P inputs. Understanding these processes is essential for developing sustainable P management strategies that improve fertilizer efficiency while reducing environmental losses.

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# Preliminary assessment of humic substances from chicken-manure hydrochar as drivers of soil microbial activity

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## ABSTRACT

Hydrochar (HC) has shown promising effects on soil biological functioning, although the mechanisms underlying these responses remain unclear. In previous greenhouse experiments, the application of 6.5 t ha$^{-1}$ of chicken-manure-derived HC to a Cambisol cultivated with sunflower increased bacterial and fungal abundance, enhanced microbial activity, shifted microbial community structure, and improved plant performance under both well-irrigated and water-deficit (WD) conditions (unpublished data). However, physicochemical characterization of the HC revealed low total organic C (5.86%) and N (0.47%), low water holding capacity (32%), and limited nutrient contents (Moreno-Racero et al., 2025), insufficient to account for the observed biological responses. These findings suggest that, beyond these bulk properties, specific labile or bioactive fractions may be responsible for the stimulation of the soil–plant–microorganism system.

Here, we present a preliminary evaluation of humic substances (HS) extracted from HC as potential drivers of these effects. HS were extracted using 0.1 M NaOH, followed by sodium removal via ion-exchange membranes, rotary evaporation (40 °C, 2 h), and lyophilization. Solid-state $^{13}$C NMR analysis showed that the extracted HS were characterized by reduced O-alkyl and N-alkyl C regions and a relatively higher proportion of aromatic C compared with the original HC.

A 77-day incubation experiment (25 °C) was conducted using the same Cambisol under well-irrigated and WD conditions. Treatments included: (i) unamended control (CTR), (ii) HC at 6.5 t ha$^{-1}$, (iii) HS equivalent to 6.5 t ha$^{-1}$ HC, and (iv) HS equivalent to 20 t ha$^{-1}$ HC. Soil microbial functioning was assessed using the MicroResp technique to determine basal respiration (BR), together with fluorescein diacetate (FDA) hydrolysis, arylsulfatase, arginine ammonification, urease, and phenol oxidase activities. HS increased BR similarly to HC and stimulated specific enzyme activities. Arylsulfatase showed a positive, dose-dependent response irrespective of irrigation regime, indicating stimulation of S cycling processes in soil (12–33% increase relative to CTR). Under WD, FDA hydrolysis increased at the higher HS dose (equivalent to 20 t ha$^{-1}$ HC) compared to CTR. The remaining enzyme activities were unaffected.

Overall, these preliminary results indicate that HS may partially account for the previously observed stimulation of microbial activity by HC, pointing to mechanisms beyond simple nutrient supply. The findings support the hypothesis that specific bioactive fractions within HC may contribute to improvements in soil microbial functioning, potentially influencing plant performance.

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# Multiple environmental stressor networks shape divergent pathways of biodiversity and ecosystem functioning in urban ecosystems.

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**ABSTRACT**

Urbanization disrupts soil ecosystems, yet the mechanisms linking biodiversity loss to the persistence of ecosystem functioning remain poorly understood. Here, we investigated how 12 urban stressors—including heavy metals, pesticides, microplastics, and macro-litter—shape soil biodiversity and ecosystem multifunctionality (EMF). Our results reveal that urban soil systems undergo a functional reorganization as the number of multistressors (nMS) increases. Biodiversity declined significantly as the number of urban stressors increased, whereas EMF remained comparatively resistant to stress accumulation. Although several ecosystem functions weakened under urban pressure, others—particularly soil fertility—remained stable or even increased. Importantly, persistent ecosystem functions were more strongly associated with chemical, climatic and urbanization pressures, including heavy metals, salinity and microplastics, than with biodiversity itself. This decoupling between biodiversity and multifunctionality suggests that urban soils can maintain aggregate ecosystem functioning despite significant biodiversity declines. Furthermore, we show that stressor networks differentially regulate biodiversity and ecosystem functions, generating divergent ecological responses across functional dimensions. These findings challenge biodiversity-centered conservation paradigms and highlight the need for urban management frameworks that recognize the growing role of these anthropogenic filters in sustaining ecosystem functioning under chronic urban stress.

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# Drivers of soil health of olive groves and their impact on the sustainable production of olive oil in the Mediterranean

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**ABSTRACT**

Olive cultivation is one of the most socioeconomically important agricultural systems in the Mediterranean Basin, yet it faces increasing threats from land degradation, climate change, and unsustainable management practices. These pressures contribute to soil erosion, biodiversity loss, and reduced agroecosystem functionality, ultimately affecting olive yield and oil quality. Despite its importance, the drivers of soil health in olive groves and their implications for sustainable production remain poorly understood.

Here, we present a comprehensive large-scale assessment of soil health in Mediterranean olive groves, integrating agronomic management, climatic conditions, soil properties, biodiversity indicators, and productivity metrics. Using multivariate analyses and network correlation approaches, we evaluated how different levels of agricultural intensification, landscape context, soil types, and the presence of soil pollutants influence soil biological communities and ecosystem functioning. Our results reveal strong associations between soil biodiversity, environmental conditions, and olive yield, highlighting the key role of soil ecological processes in sustaining production. Furthermore, we identify critical drivers shaping soil health and demonstrate how management practices can either enhance or compromise ecosystem services.

This integrative approach provides novel insights into the mechanisms linking soil health and agricultural sustainability in Mediterranean olive systems, offering valuable guidance for management strategies to improve resilience, productivity, and environmental sustainability under ongoing global change.

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# Towards the identification of microbial indicators of soil health: a one-year field study in a Mediterranean olive grove

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**ABSTRACT**

Worldwide, approximately 50,000 km² of fertile soil are lost each year; largely as a consequence of inadequate land management practices. Soil degradation may result from insufficient vegetation cover, complete removal of vegetation cover, excessive tillage, over-irrigation, or the intensive use of fertilizers. These factors, together with the increasing frequency of extreme weather events, underscore the urgent need to monitor both land use practices and soil health. In this context, continued investigation of the soil microbiome under different management regimes is essential to anticipate ecosystem changes and to identify reliable bioindicators of soil quality. Advancing our understanding of soil status requires deeper knowledge of microbial community composition and its responsiveness to management practices.

To address this, we selected soils from an olive grove located in southern Spain subjected to three contrasting management regimes: conventional tillage (CT), mixed vegetation cover (MC), and herbicide application along the tree line (TL-Herb). Olive cultivation represents one of the most widespread agricultural systems in the Mediterranean basin, making its sustainable management particularly relevant. Moreover, olive groves are often established on sloping terrain, where inappropriate management can exacerbate erosion and accelerate soil loss. To evaluate potential topographic effects, samples were collected separately from the upper and lower positions within each plot. Seasonal variability was also considered by conduction sampling across all four seasons.

A comprehensive soil characterization was performed, including measurements of pH, electrical conductivity, macro- and micronutrient content, phospholipid fatty acid (PLFA) profiles, and 16S rRNA gene sequencing. This study presents the results with particular emphasis on differences in microbial community structure. Preliminary analyses indicate that plots with vegetation cover showed the highest microbial biomass, with the most pronounced seasonal differences observed in spring and autumn. Taxonomic shifts were also detected, including an increase in Actinomycetota in the upper slope positions and a decrease in Bacillota in the lower slop areas under conventional tillage and vegetation cover treatments. These findings will be complemented by effect size analyses integrating all measured soil parameters to assess their relative contribution to microbiome composition and to identify potential indicators of soil health.

**Acknowledgments**

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# Study of coumarins trafficking in Arabidopsis thaliana

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**ABSTRACT**

Iron is an essential micronutrient for plant growth and development, as well as for crop productivity and the quality of their derived products. Despite its abundance in the Earth's crust, iron is often poorly available to plants, particularly at neutral to alkaline pH, which account for one-third of cultivated lands. To cope with this poor bioavailability, plants have evolved sophisticated mechanisms to mine iron from the soil. Recently, it has emerged that non-grass species secrete iron-mobilizing coumarins (specialized metabolites derived from the phenylpropanoid pathway) by the plant root system, via the PDR9/ABCG37 transporter, to improve Fe uptake (Robe et al., 2025). The secretion of iron-mobilizing coumarins is a complex and dynamic process that most probably involves several transporters (Robe et al., 2021; Watanabe et al., 2026). My project focuses on understanding the dynamics of coumarin transport by identifying and characterizing the molecular actors involved, through the characterization of newly isolated loss-of-function *Arabidopsis thaliana* mutants, and by setting up a genetic screen.

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# Inorganic and Organic Carbon Stocks in Semi-Arid Perennial Systems: The Role of Cover Crops

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## ABSTRACT

Agriculture offers significant potential for carbon sequestration when sustainable management practices are adopted, thereby contributing to atmospheric $CO_2$ removal. A clear example is the use of spontaneous cover crops in perennial systems such as olive orchards. These crop types not only play a key role in carbon management but also underpin the socio-economic and cultural fabric of many regions in Andalusia, where they shape the dominant agricultural landscape. Most research assessing the effects of cover crops has primarily focused on soil organic carbon (SOC) dynamics, often overlooking the potential influence of this practice on inorganic carbon (SIC) pools. This gap is particularly significant because Mediterranean regions, where these perennial crops are commonly grown, SIC stocks can exceed SOC by several times. The global objective of this study was to quantify the stocks of soil organic and inorganic carbon and explore the changes in soil aggregation distribution and associated carbon after cover crop implementation under rainfed conditions. To accomplish it, fifteen paired commercial olive orchards under different soil management practices in the inter-tree rows (bare soil, NCC *vs.* vegetation cover, CC, for at least ten years) and representing a gradient of precipitation (200-900 mm) and soil pH (7.5 to 8.8) conditions were selected. In each of the CC and NCC olive groves, six soil samples were taken to analyze soil physical-chemical properties, including organic and inorganic carbon and biomass. Preliminary results indicate that about 90% of the total carbon was the inorganic carbon in these soils. CC implementation increased SOC and decreased the SIC stocks in about 56% and 15%, respectively, in the first 30 cm of soil. Two of the fifteen paired olive orchards displayed a different trend with an increase in the inorganic carbon stock (between 17 and 112%) with the CC management. SOC stock depended on the presence/absence of cover crops and local conditions, but no interaction between location and management was detected. Greater differences in SOC stock between CC and NCC were generally observed in those fields with higher mean annual precipitation and elevated soil carbonate content. In contrast, differences in SIC stock between CC and NCC were not related neither with precipitation nor with soil pH. A significant increment (between 21 and 111%) in the percentage of macroaggregates (>250µm) and organic carbon occluded in all the aggregates fractions (macro, micro and silt plus clay) were observed under cover crops. Moreover, no interaction between location and management was observed for the aggregate distribution, whereas a significant interaction was detected for occluded OC.

**Acknowledgments**

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# Microbial community shifts reveal the multifunctional potential of biobased fertilizers in Mediterranean calcareous soils

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**ABSTRACT**

The use of biobased fertilizers is increasingly promoted as a sustainable alternative to mineral fertilization. However, their effects on soil microbial biodiversity remain insufficiently characterized, particularly in Mediterranean calcareous soils where high carbonate content and drought constrain nutrient phytoavailability, including phosphorus (P). This study evaluated the impact of five biobased fertilizers on soil physicochemical properties, nutrient dynamics, and bacterial and fungal community structure during two cropping seasons (wheat-sunflower rotation) in southern Spain under calcareous conditions (Vertisol). The tested biobased fertilizers included Commercial Plant Residue (CPR), composted Digestate (DIG), composted Olive Mill Pomace (OMP), composted Urban Organic Waste (UOW), and Vermicompost (VER), and were compared with a mineral P fertilizer (Diammonium Phosphate, DAP) and a non-fertilized control (CON). The objectives were: (i) to assess whether biobased fertilizers enhance soil functions beyond plant productivity (particularly P cycling, organic matter dynamics, habitat provision, and microbial biodiversity), and (ii) to evaluate their potential to replace mineral P fertilizers under Mediterranean conditions. Biobased fertilizers exhibited distinct nutrient release patterns driven by their composition. UOW produced the highest increases in available P, Zn ($Zn_{DTPA}$), and Fe ($Fe_{DTPA}$), as well as crop P use efficiency at the end of the field experiment. Both UOW and OMP significantly increased soil organic matter content after sunflower's harvest. Fungal community shifts were associated with increases in soil organic carbon (C), total nitrogen (N), and C:N ratio, suggesting links between biobased fertilizers and fungal-driven C cycling. In a multivariant analysis (PCA), UOW showed a strong correlation with plant available P, $Zn_{DTPA}$, $Fe_{DTPA}$, and microbial taxa related to nutrient mobilization and turnover, including *Novibacillus*, *Melghirimyces*, *Microascus*, and *Bryobacter*. Overall, biobased fertilizers enhanced key soil functions (nutrient and organic matter cycling), while supporting microbial community in increasing soil nutrient availability and enhancing soil health in a calcareous Mediterranean soil. Among the tested biobased fertilizers, UOW and OMP showed the greatest multifunctional potential, highlighting their suitability as sustainable alternative to mineral P fertilizers in wheatsunflower rotations of southern Spain.

**Acknowledgments**

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# Linking nematode community dynamics to soil functioning across agronomic practices

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## ABSTRACT

Soil health is the capacity of soil as a living system to provide essential ecosystem functions, including carbon and climate regulation, water purification, nutrient cycling, biodiversity conservation, and plant productivity. Soil health is affected by agronomic practices by altering soil physical and chemical properties, and biological activity. Nematodes are key players in soil processes and are increasingly used as bioindicators of soil health, particularly to assess disturbance and biodiversity. However, the mechanistic linkage between nematode communities and ecosystem functioning is poorly investigated, and whether nematode-based indices (NBIs) can serve as effective indicators of overall soil health and specific soil functions remains unconfirmed.

This study aims to determine how nematode community structure response to long-term agronomic practices (fertilization type and tillage intensity) and to evaluate whether NBIs can predict soil ecosystem functioning in a temperate agriculture system.

We investigate a 4-year rotation system including mineral NPK fertilizer, two digestate products (dried digestate without manure and biothermal organic waste), compost, manure and a second field with different tillage intensity and compost input. Soil cores will be collected four times per year over two consecutive years. Nematode abundance and community structure will be assessed at family/genus level using morphological and molecular approaches. Functional indices, metabolic footprint, and carbon and energy fluxes through the nematode food web will be calculated and integrated with rate measurements of soil carbon cycling, nitrogen transformation, pathogen suppression, and plant growth.

By linking nematode community dynamics to multiple ecosystem functions, this study will shed new light in understanding their regulatory role in various soil processes and provide a solid foundation of nematodes as effective indicators of soil health.

# Andean K'allanp' Community: Navigating mycorrhizal community stewardship of Biocultural Andes, Chichupampa Clan, Cotacachi, Imbabura, Ecuador.

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**ABSTRACT**

Soil health is the result of complex interactions between biogeochemical processes, microbial biodiversity, and culturally situated management practices. This work presents a research experience supported by the Society for the Protection of Underground Networks (SPUN) that uses environmental DNA (eDNA) to analyze soil microbial communities under Indigenous agricultural practices in Andean and Amazonian territories of Ecuador. These practices, based on principles of reciprocity, diversification, and stewardship of the land, offer a living framework for understanding how Indigenous management influences the structure and function of soil microbial networks.

The study is being conducted through an intercultural alliance between Indigenous communities, local scientists, and specialists trained in dominant Western scientific traditions (WEIRD). The use of eDNA allows for the generation of high-resolution data on microbial biodiversity and subsurface networks, while Indigenous knowledge guides the ecological interpretation of the results, contextualizing them within biocultural agri-food systems and long-term climate adaptation strategies.

This collaborative approach challenges extractive research models and proposes a more biocultural, relational, and inclusive soil science, where molecular data and ancestral knowledge are co-produced and interpreted in a complementary manner. Preliminary results suggest that Indigenous practices not only support high microbial diversity but also strengthen key ecosystem functions, contributing to soil resilience in the face of climate change.

The study demonstrates how eDNA, when ethically integrated with Indigenous practices and intercultural collaboration, can expand the frontiers of soil microbial ecology and support sustainable and culturally situated management of soil resources.

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